

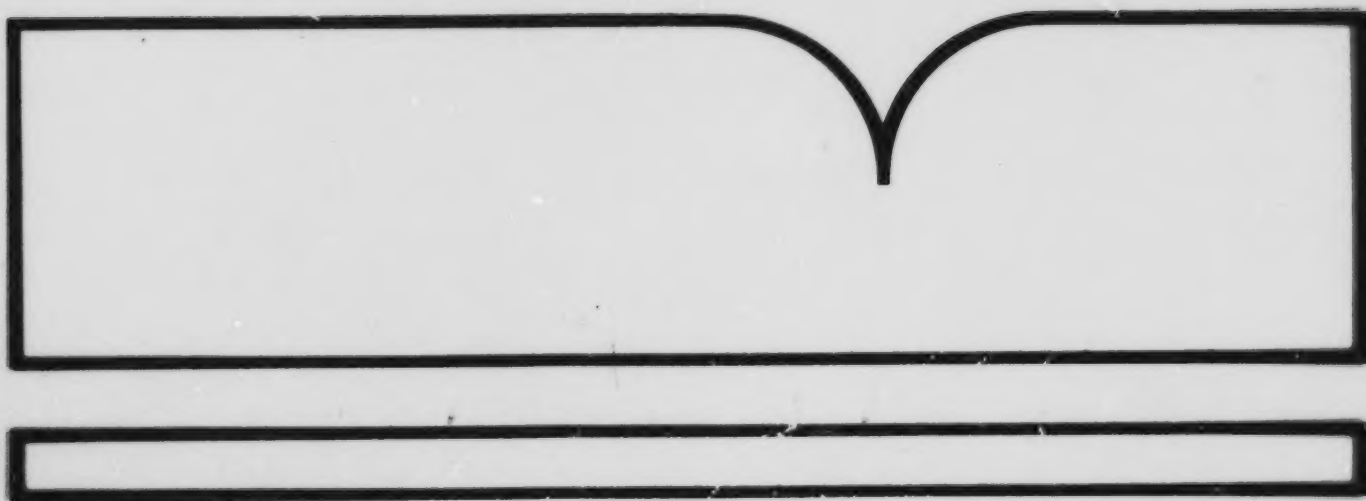
Flare Efficiency Monitoring by Remote  
Infrared Sensing: A Feasibility Demonstration

OptiMetrics, Inc., Bedford, MA

Prepared for

Industrial Environmental Research Lab.  
Research Triangle Park, NC

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**NTIS**

FLARE EFFICIENCY MONITORING BY REMOTE  
INFRARED SENSING: A FEASIBILITY DEMONSTRATION

by

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| 16. ABSTRACT The report gives results of an evaluation, involving field tests, of passive infrared methods for use in remotely monitoring the efficiency of industrial flares. The tests utilized a general infrared measurement device, the EPA ROSE (Remote Optical Sensing of Emissions), a Fourier transform infrared (FTIR) system. With this system, infrared emissions from the gaseous exhaust products of a small scale industrial flare were observed under a wide range of operating conditions, at several positions in and above the combustion zone. Major results of this evaluation include: (1) collection of a data base on flare emissions for a typical flare at several flow rates of propylene, steam, and nitrogen; (2) comparison of three runs with simultaneous extractive probe measurements indicating comparable CO and CO2 concentrations (to within 10-30%) but significantly different temperatures (differing by a factor of 2 to 4); (3) determination of a better than 20 ppm detection threshold for CO using FTIR; and (4) the conclusion that the most serious uncertainties are the spatial distributions of temperature and gas concentration, and the detectability of hydrocarbon species. |                   |                                                              |                        |
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| Pollution                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Infrared Equip-   | Pollution Control                                            | 13B                    |
| Flammable Gases                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | ment              | Stationary Sources                                           | 11G 17E, 20F           |
| Exhaust Gases                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Measurement       | Industrial Flares                                            | 21B                    |
| Combustion                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Optical Equipment |                                                              |                        |
| Efficiency                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Carbon Monoxide   |                                                              | 14G 07B                |
| Monitors                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Carbon Dioxide    |                                                              |                        |
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## ABSTRACT

Passive, infrared methods have been evaluated for use in remotely monitoring the efficiency of industrial flares. To perform this evaluation, a series of field tests were conducted using a general infrared measurement device, the EPA ROSE, Fourier Transform Infrared (FTIR) system. With this system, infrared emissions arising from the gaseous exhaust products of a small scale industrial flare were observed under a wide range of operating conditions at several positions in and above the combustion zone. A procedure was developed by which carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) concentrations could be determined from these emissions, and the results were used to estimate flare efficiency. The procedures developed utilize basic spectroscopic principles, mainly the use of the vibration-rotation lines of the CO fundamental emission band to calculate an approximate gas temperature followed by a "best-fit" matching of computer-modeled CO and CO<sub>2</sub> synthetic spectra to the measured spectra in order to determine CO and CO<sub>2</sub> concentrations. These concentrations are then combined to estimate flare efficiency.

The major results of this study include: a) the collection of a data base on flare emissions for a typical flare at several flow rates of propylene, steam and nitrogen; b) the comparison of three specific runs with simultaneous extractive probe measurements indicating comparable carbon monoxide and carbon dioxide concentrations (to within 10 to 30 percent) but significantly different temperatures (differing by a factor of 2 to 4); c) the determination of a better than 20 ppm detection threshold for CO using FTIR; and d) the conclusion that the most serious uncertainties are the spatial distributions of temperature and gas concentration, as well as the detectability of hydrocarbon species.

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## LIST OF ABBREVIATIONS AND SYMBOLS

### ABBREVIATIONS

|                  |                                                       |
|------------------|-------------------------------------------------------|
| ATLES            | -- Atmospheric Transmission for Line Emission Sources |
| cm               | -- centimeter                                         |
| cm <sup>-1</sup> | -- reciprocal centimeter                              |
| EFF              | -- efficiency                                         |
| FASCOD1          | -- Fast Atmospheric Signature Code                    |
| ft/min           | -- feet per minute                                    |
| FFT              | -- fast Fourier transform                             |
| FTIR             | -- Fourier transform infrared                         |
| lbs/hr           | -- pounds per hour                                    |
| ppm              | -- parts per million                                  |
| ROSE             | -- Remote Optical Sensing of Emissions                |
| sec.             | -- seconds                                            |
| STER             | -- steradian                                          |
| temp.            | -- temperature                                        |

### SYMBOLS

|                 |                                                                          |                 |                                                                          |
|-----------------|--------------------------------------------------------------------------|-----------------|--------------------------------------------------------------------------|
| $A_r$           | receiver telescope area                                                  | R               | R-branch transition for molecular vibration-rotation quantum number = -1 |
| B               | background (subscript)                                                   | r               | spectral reflectivity                                                    |
| B'              | spectroscopic rotational constant                                        | S               | signal amplitude                                                         |
| BB              | signal due to blackbody source                                           | SPEC            | signal due to spectrometer self-emission                                 |
| BKG             | signal due to background                                                 | SO <sub>2</sub> | sulfur dioxide                                                           |
| c               | speed of light                                                           | T               | temperature                                                              |
| CH <sub>4</sub> | methane                                                                  | T               | terrain, buildings (subscript)                                           |
| CO              | carbon monoxide                                                          | THC             | total hydrocarbons                                                       |
| CO <sub>2</sub> | carbon dioxide                                                           | V-R             | vibration-rotation                                                       |
| E <sub>R</sub>  | rotational energy                                                        | X               | radial position in plume                                                 |
| E <sub>V</sub>  | vibrational energy                                                       | °K              | degrees Kelvin                                                           |
| F               | foreground (subscript)                                                   | ε               | spectral emissivity                                                      |
| h               | Planck's constant                                                        | ℓ               | optical path length                                                      |
| I               | spectrometer (subscript)                                                 | ν               | wave number                                                              |
| J               | rotational quantum number                                                | ω               | solid angle of field-of-view                                             |
| K               | spectroscopic constant                                                   | %               | percent                                                                  |
| N <sub>ν</sub>  | spectral radiance                                                        | τ               | spectral transmissivity                                                  |
| NO <sub>x</sub> | oxide of nitrogen                                                        | τ'              | spectral transmission for scattering                                     |
| P               | P-branch transition for molecular vibration-rotation quantum number = -1 | [ ]             | concentration                                                            |
| P               | spectral power                                                           |                 |                                                                          |
| p               | partial pressure                                                         |                 |                                                                          |
| R               | response                                                                 |                 |                                                                          |

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## SECTION 1

### INTRODUCTION

Flares are used by a number of industries for the disposal of waste gases by combustion. The total amount of gas flared in the U.S. has not been measured accurately, but one estimate is 16 million tons per year (1). Since large amounts of gases are flared, both the Government and the associated industries have a vital interest in ensuring that the design and operation of flare systems are optimum in order to minimize the production of undesirable by-products.

Therefore, a need exists for the development of an effective means by which flare efficiency can be monitored. Two of the potential measurement approaches for determining flare efficiency are:

- 1) point sampling of combustion products using extractive probes, and
- 2) remote sensing of combustion products using infrared spectroscopic techniques.

Each approach has strengths and weaknesses. The extractive probe provides localized data on a large number of exhaust species in a very direct manner; however, the local nature of the probe measurement makes it vulnerable to wind effects unless compensation is provided by including a tracer gas. That is, variations in concentrations observed with a probe could be caused by the wind moving the combustion products relative to the probe, or be simply attributable to spatial variations in the plume itself. In addition, the probe is a direct measurement requiring that the apparatus be at the flare itself, introducing possible interferences with plant operation.

The remote sensing concept utilizes the fact that the exhaust products employed in the efficiency calculation are infrared-active. This means that each has its own unique radiant emission (or signature) in the infrared region of the spectrum. This "signature", being related to the concentration of the product, allows infrared spectroscopy to be used to determine flare efficiency by measuring these radiant emissions remotely and non-obtrusively. The infrared method is also more global in the sense that a spatial averaging is obtained. Consequently it may provide a more representative measure than a localized probe.

## APPLICABILITY OF REMOTE INFRARED SENSING FOR FLARE MONITORING

To define the problem properly, we should consider what is meant by flare efficiency. There are a number of different definitions of efficiency, some of which require the use of trace compounds added to the flare fuel, while others require the monitoring of plant activity in one way or another. Some of these are local in the sense of performing point sampling of localized areas of the plume over a short time interval, while others are global, requiring either integration of local samples or collection of all the exhaust products.

Extractive probe techniques use the term "combustion efficiency," which is based on the oxidation of flare emissions to carbon dioxide. It is defined as (2):

$$EFF \equiv \frac{[CO_2]}{[CO_2] + [CO] + [THC] + [Soot]} \quad (1)$$

where

$[CO_2]$  = parts per million by volume of carbon dioxide,

$[CO]$  = parts per million by volume of carbon monoxide,

$[THC]$  = parts per million by volume of total hydrocarbon as methane, and

$[Soot]$  = parts per million by volume of soot as carbon.

The same definition was adopted for our remote sensing technique, except the soot term was deleted because soot could not be monitored directly with the available infrared equipment. Fortunately few of the tests studied had significant soot loadings. Furthermore, the sensitivity of the ROSE system, coupled with the small optical depths of the flare studied, were insufficient for measuring hydrocarbon radiant emissions. This necessitated using an approximation to Equation 1 depending only upon carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) as:

$$EFF \approx \frac{[CO_2]}{[CO_2] + [CO]} \quad (2)$$

Since, in general, the total hydrocarbon concentration is small compared with that of CO and CO<sub>2</sub> at high efficiencies, this approximation is appropriate for evaluation of flare operation in the high efficiency regime, such as that encountered with most industrial flares.

## SCOPE OF STUDY

As suggested above, remote optical sensing offers great promise for flare efficiency monitoring. While numerous previous efforts have demonstrated its value for the general field of air pollution, only limited efforts have been undertaken to evaluate it specifically for flare efficiency measurements (3). Therefore, OptiMetrics, Inc. performed a measurements and analyses effort for the Environmental Protection Agency (EPA) to demonstrate and develop remote optical sensing, specifically infrared spectroscopy, for application to this monitoring problem.

Infrared spectroscopic data were collected by OptiMetrics at the John Zink Company, Tulsa, Oklahoma, from 17 to 24 June 1982. The measurements were made in conjunction with a series of flare tests conducted by Engineering Science, Inc. and sponsored by EPA and the Chemical Manufacturers Association (CMA). The instrumentation used by OptiMetrics was the EPA ROSE (Remote Optical Sensing of Emissions) system, which is a versatile spectroscopic measurement tool containing a Fourier transform infrared (FTIR) spectrometer as well as computer-based data collection and processing equipment (4, 5).

In addition to the infrared measurements performed by OptiMetrics, coincident extractive probe measurements were obtained by Engineering Science, Inc. which could be used for comparison. These measurements provided localized data on gas temperatures as well as on the concentrations of various combustion products, including CO, CO<sub>2</sub>, hydrocarbons and particulates. Since these probe measurements represent the current state-of-the-art in flare emission monitoring, they were compared with the FTIR results to estimate the basic validity of the infrared approach. To facilitate these comparisons, the majority of the remote infrared data was taken at the same position and at the same time as that of the probe.

A further comparison of FTIR and probe data was performed using a set of five (5) "unknown" calibration gases whose identities and concentrations were determined both by the extractive probe analysis methods and by absorption measurements using the ROSE FTIR. These comparisons were used to determine the inherent agreement between the two measurement methods independent of flare or atmospheric influences.

## REPORT CONTENTS

This report is intended to provide an understanding of remote optical sensing and infrared spectroscopy as applied to the problem of flare monitoring as well as to present experimental results from actual flare measurements.

It is divided into several sections with major topics outlined below:

## SECTION 2: CONCLUSIONS AND RECOMMENDATIONS

- \* Summarizes the conclusions resulting from the test program, proposes additional studies to improve and verify the methodology, and indicates the potential applicability of these methods to other measurement scenarios.

## SECTION 3: PRINCIPLES OF INFRARED MEASUREMENTS OF FLARES

- \* Provides an outline of the basic concepts of molecular spectroscopy, a description of the instrumentation used, and a discussion of the general applicability of remote sensing to flare monitoring.

## SECTION 4: FIELD MEASUREMENTS OF A TYPICAL SMALL SCALE FLARE

- \* Discusses the experimental procedures and instrumentation employed to collect the flare emission data.

## SECTION 5: DEVELOPMENT OF FLARE EFFICIENCY CALCULATION METHODOLOGY

- \* Presents details of the analysis methodology and the results of its application to actual flare data.

## APPENDIX A: INFRARED ANALYSIS OF "UNKNOWN" CALIBRATION GASES

- \* Describes and presents results of a cross-calibration effort comparing the extractive probe and FTIR methods.

## APPENDIX B: RECOMMENDED FURTHER WORK TO IMPROVE AND VERIFY METHODOLOGY

- \* Presents a number of the critical issues which should be addressed in future work, as well as recommendations on how they should be addressed.

## SECTION 2

### CONCLUSIONS AND RECOMMENDATIONS

#### PROGRAM RESULTS

Experimental data were collected on a small scale industrial flare using remote IR methods. These data were then used to develop a baseline analysis procedure for determination of specie concentrations required for the evaluation of flare combustion efficiency. Once developed, these baseline methods were applied to four specific tests and the results compared with point-sampling measurements to determine the basic applicability of the IR approach.

In general, the results of these comparisons clearly indicate that IR methods are applicable to the problem of combustion efficiency monitoring and, in many instances, they can offer substantial advantages over currently available methods. Even with the limited developmental work possible in this study, baseline procedures could be formulated which allowed for evaluation of plume temperature, CO concentration, and CO<sub>2</sub> concentration based solely on the IR spectra. With these values, estimates of efficiency could then be made using the approximate relationship of equation (2), which at high efficiency gave values in good agreement with the point sampled results, (see Table 1). The only major shortcoming of the IR approach was its

TABLE 1. COMPARISON OF REMOTE SENSING EXTRACTIVE PROBE SAMPLING (6)

| Test No. | Temp. (°K) |       | CO<br>Concen. (ppm) |       | CO <sub>2</sub><br>Concen. (ppm) |       | THC<br>Concen. (ppm) |       | Efficiency(%) |       |
|----------|------------|-------|---------------------|-------|----------------------------------|-------|----------------------|-------|---------------|-------|
|          | FTIR       | Probe | FTIR                | Probe | FTIR                             | Probe | FTIR                 | Probe | FTIR          | Probe |
| 50       | 920        | 416   | <20                 | 35    | 6000                             | 5382  | xx                   | 17    | >99.67        | 99.1  |
| 53       | 1400       | 387   | <27                 | 18    | 2900                             | 2438  | xx                   | 7     | 99.08         | 99.0  |
| 55       | 683        | 344   | 155                 | 125   | 1800                             | 1371  | xx                   | 475   | 92.07         | 69.7  |
| 59*      | 2500       | 421   | 1350                | 80    | >6000                            | 5965  | xx                   | 63    | >81.63        | 97.7  |

\* FTIR in combustion flame, probe above, both above flame in others.

xx Not measurable by FTIR.

Note: Probe data are background corrected; over the same observation time as the FTIR values.

inability to determine total hydrocarbon concentrations which are necessary for monitoring lower efficiency flares. This was in part the result of using a general IR instrument not specifically tailored to this measurement problem and in part the result of looking at a small flare, with limited optical depth, rendering the detection of weaker IR emitters difficult. Given a solution to this problem, however, IR methods look attractive because they allow for remote, non-hazardous, non-intrusive monitoring of industrial type flares from distances as large as 1/4 to 1/2 mile. The methodologies developed also look straightforward enough that they could be implemented on field hardware, allowing for near real-time, in-situ results. In addition, it is highly probable that less costly and more selective IR equipment could be developed for use in monitoring the specific species of interest.

#### GENERAL APPLICABILITY OF FTIR TO FLARE MONITORING

From the experience and results of this program, we conclude that the FTIR approach, although not fully developed at this time, clearly has some distinct advantages over conventional monitoring methods:

- 1) The operation is remote as well as passive. It therefore minimizes potentially objectionable interference with normal plant operation, eliminates the need for personnel being in close proximity to a large industrial flare, and makes possible sampling of elevated flares from an off-site location.
- 2) The approach allows for great flexibility in choosing operational parameters. For example, the spectral resolution, collecting area, spectral range and measurement time can be easily adjusted in real-time to accommodate variations in flare operation, as well as to facilitate both local and spatially averaged observations.
- 3) Monitoring of a number of separated flares can be accomplished in a timely manner from a central measurement facility.
- 4) FTIR can accommodate a variety of flare sizes. The performance will in fact increase with size since, for the same spectrometer sensitivity, a longer optical path results in a lower detection threshold.
- 5) Monitoring equipment can be operated by one person, and there is potential for automated, in-situ data analysis. Therefore, labor costs are minimal, even though initial equipment costs may be relatively high.

Confidence in the results and conclusions derived from FTIR data are provided by the fact that the basic principles and methods are well established, although the specific analysis techniques are not yet perfected for application to flares. The greatest uncertainty in this regard is the lack of an accurate knowledge of the spatial distributions associated with temperature and specie concentrations for a "typical" flare.

#### RECOMMENDATIONS

From the limited but positive results achieved in this study, it can be concluded that remote infrared spectroscopy is a viable and, in some ways, advantageous means of monitoring flare efficiency. However, the results also suggest that further work is required to refine and verify the methodology in several areas. Recommendations for additional tests and analyses therefore include:

- a) comparisons of FTIR results with extractive probe or alternative measurements, under more highly controlled conditions,
- b) performance of vigorous sensitivity and accuracy analyses for the developed IR methodology,
- c) determination of spatial distributions for temperature and concentration within typical flares, and
- d) investigation of the use of automated monitoring procedures with simplified versions of spectra fitting and less expensive IR hardware.

### SECTION 3

#### PRINCIPLES OF INFRARED MEASUREMENTS OF FLARES

##### SPECTROSCOPIC PRINCIPLES

Molecules such as those of interest in flare monitoring may be considered as energy carriers. This energy may take several different forms and, in general, a molecule will have some of each. Two of these forms are rotational energy ( $E_R$ ) and vibrational energy ( $E_V$ ). When the gas molecule interacts with the ambient environment, it generally undergoes an energy change and electromagnetic radiation may be either absorbed or emitted by the molecule.

Quantum mechanics tells us that a molecule may have only certain discrete values of  $E_R$  and  $E_V$  and that only certain transitions between the possible energy states are "allowed." Both the "allowed" energy levels and the "allowed" transitions are unique for each molecule. Since the optical frequency (the reciprocal of the wavelength) of the electromagnetic radiation absorbed or emitted by a molecule is proportional to the energy difference between the levels involved in the transition, the several transitions combine to form a pattern of lines or a spectrum unique to each molecular specie. As the magnitude of the energy change is the same whether the transition is from lower to upper or from upper to lower energy states, the spectral line due to a given transition has the same frequency or wavelength both in emission and absorption.

The transitions of interest in the current remote sensing study are vibration-rotation transitions which occur in the near and middle infrared and form line groupings called vibration-rotation (V-R) bands. These bands only exist if the molecule has a permanent or induced dipole moment. Fortunately,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ , etc. are such molecules.

Diatomic V-R bands, such as that of  $\text{CO}$ , have two branches, the P branch and the R branch, consisting of the various rotational transitions possible with a constant vibrational energy change. Between these two branches is an area devoid of lines, which is the band center. The individual rotational energy levels, which are unique to each molecule, are specified by the quantum number  $J$ . For diatomic molecules, the only transitions allowed are those with:

$$\Delta J = J' - J'' = \pm 1 \quad (3)$$

where  $J'$  refers to the upper rotational state and  $J''$  to the lower. In the resultant spectrum, the P branch contains those lines for which  $\Delta J = -1$ , while the R branch contains those for which  $\Delta J = +1$ . Each line is consequently identified by its branch and its rotational quantum number in the lower vibrational state. For example, P(4) is the transition between  $J' = 3$  and  $J'' = 4$ , while R(4) is that between  $J' = 5$  and  $J'' = 4$ .

Since the energy levels are unique to each molecular specie, the transitions and hence the resulting spectrum is also unique. The presence of a given specie may therefore be detected by looking for this characteristic spectrum. A typical example is shown in Figure 1, showing both CO and CO<sub>2</sub> bands.

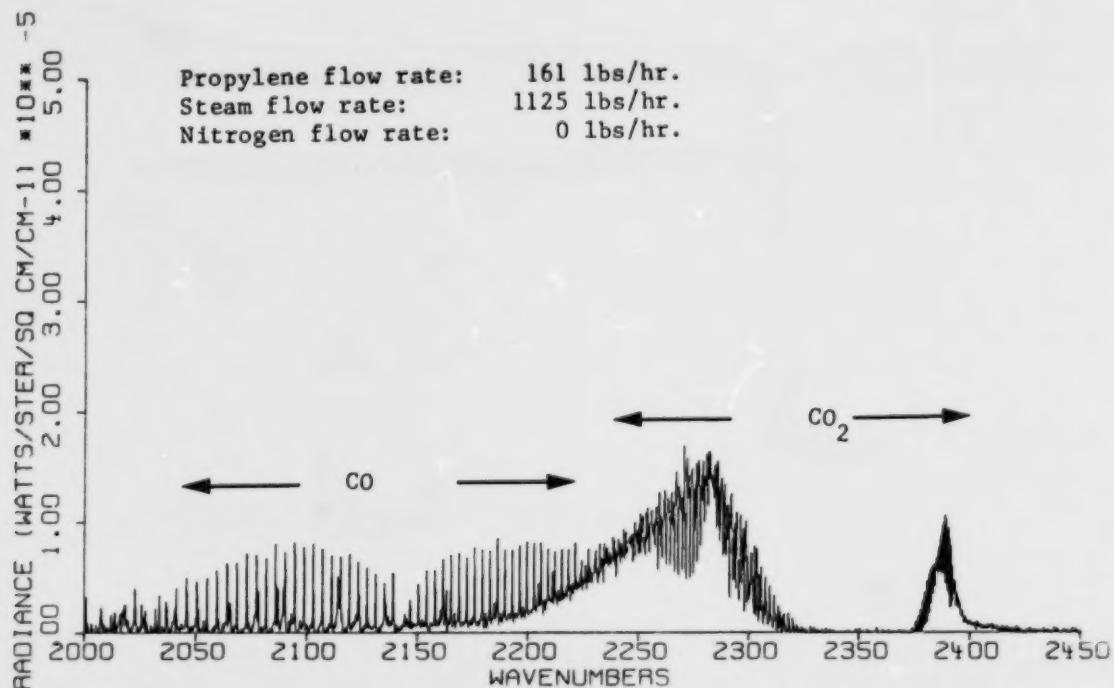


Figure 1. Observed flare emission for test 55.

For an isothermal, homogeneous path, Beer's law states that the intensity of the lines in a given band are a function of:

- the path length,  $\ell$ ,
- the absorption coefficient (a well-known spectroscopic constant specific to each gas)  $K(\nu)$ , and
- the partial pressure (or concentration) of the gas,  $p$ .

If the gases under observation are hot so that they are radiating energy, the intensity of the radiation emitted ( $N'$ ) is related to the gas concentration by:

$$N'(\nu) = (1 - e^{-K(\nu)P\ell})N_{BB}(\nu) \quad (4)$$

where  $N_{BB}(\nu)$  is the "blackbody" radiance corresponding to the temperature of the gas. Consequently, the concentration is given by:

$$P = \frac{-\ln(1 - N'(\nu)/N_{BB})}{K(\nu)\ell} \quad (5)$$

In theory, therefore, the gas concentration can be calculated from:

- a) spectroscopic measurement of the intensity of a gas emission line,
- b) the absorption coefficient for this line obtained from previous laboratory measurements, and
- c) a measurement of the optical path of the measurement along the line of sight.

In addition, one must also account for potential emission sources other than the flare itself as well as the transmission properties of the intervening atmosphere through which the flare is viewed. Therefore, the interpretation of infrared measurements for extraction of gas concentrations and flare efficiency requires an understanding of the radiative transfer process involved in propagating the plume radiance to the sensor.

#### RADIATIVE TRANSFER PROCESS

Figure 2 illustrates the potential emission sources for a typical measurement scenario and indicates the paths this radiation takes in getting to the spectrometer. The sun and the foreground contribute energy which is both transmitted through the plume and scattered by it. The background similarly contributes energy, some of which arises from directly behind the plume and is consequently received only after transmission through it, while some arise from outside the plume, yet within the field of view of the spectrometer, so that it is affected only by the atmosphere. All these contributions must then be transmitted through the intervening atmospheric path from the flare to the spectrometer in order to be detected.

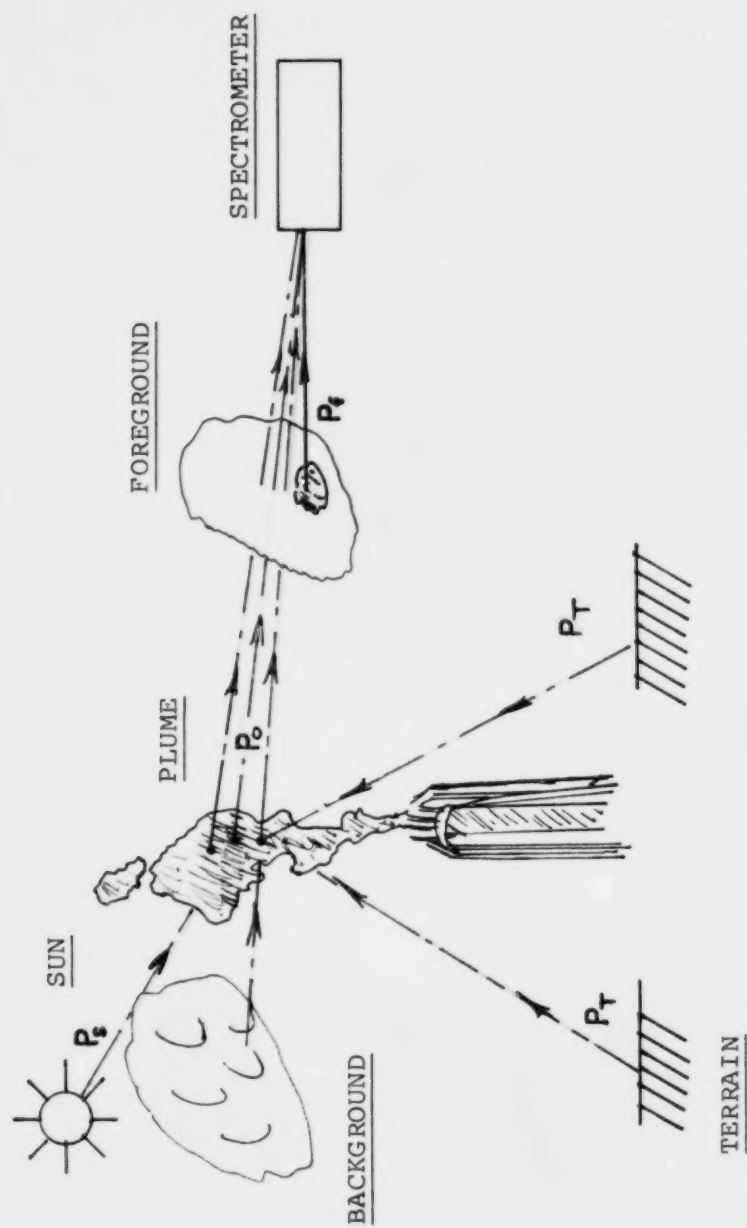


Figure 2. Emission sources.

For the flare itself, as depicted in Figure 3, various species are present, such as carbon dioxide, carbon monoxide, and methane as well as other hydrocarbons, which are in a column-like flow surrounded by flow eddies. To a first approximation, the temperature and individual concentrations for these species are greatest in the center of the "column" at its base. These then decrease both radially and axially toward ambient, primarily because of mixing with the surrounding air.

The relative contribution of each of the above elements will vary, depending on: plume temperature and species concentration, the field-of-view of the instrument, and (for scattering) on the solar angle. However, considering all potential elements to be contributing, one may represent the measured plume spectrum as:\*

$$P_P = P_O + P_F + P_B + P_S + P_T \quad (6)$$

where the energy sources are:

$$\text{plume, } P_O = N_P \epsilon_P \tau_F \theta_I \quad (7)$$

$$\text{foreground, } P_F = N_F [1 - \tau_F] \theta_I \quad (8)$$

$$\text{background, } P_B = N_B \epsilon_B \tau_B \tau_F \theta_I \quad (9)$$

$$\text{solar scattering, } P_S = N_S \epsilon_S r_P \tau'_P \tau_F \theta_I \quad (10)$$

$$\text{surrounding terrain, } P_T = N_T \epsilon_T r_T \tau'_P \tau_F \theta_I \quad (11)$$

while

$p$  = spectral power received at the spectrometer

$N$  = spectral radiance of source element

$\epsilon$  = spectral emissivity

$\tau$  = spectral transmissivity

$\tau'$  = spectral transmission for scattering

$r$  = spectral reflectivity

$\theta_I$  = throughput (spectrometer area times acceptance angle)

$B$  = subscript denoting background

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\* at wavenumber,  $\nu$

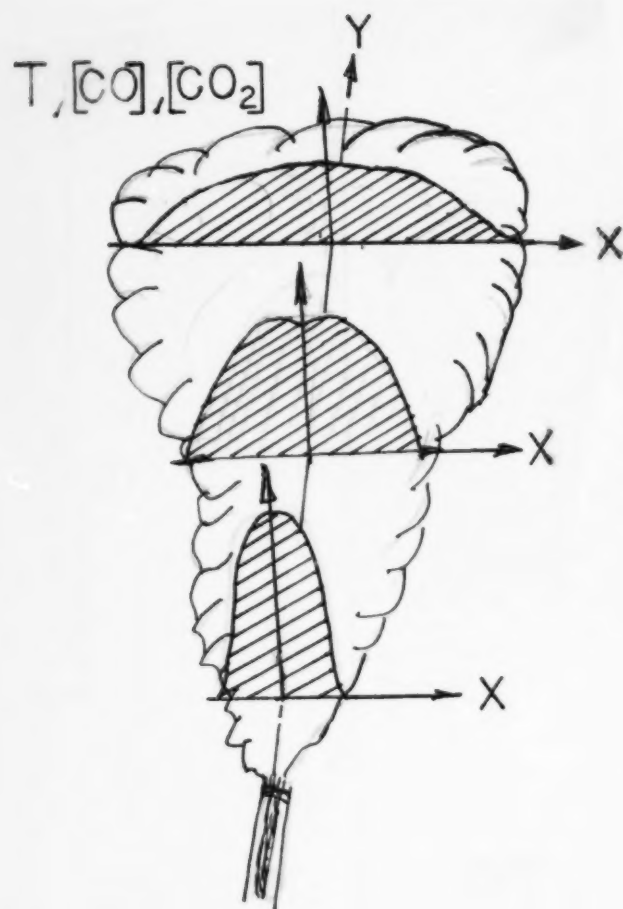


Figure 3. Idealized relative concentration and temperature profiles.

- P = subscript denoting flare plume  
T = subscript denoting terrain, buildings  
F = subscript denoting foreground  
I = subscript denoting spectrometer.

For the application of interest here, involving near infrared measurements of elevated temperature sources, the only significant contributions to the observed signal are plume emissions, background radiance, and possibly solar scattering. If the plume is at a high temperature and is relatively free of particulates, background radiance and solar scattering will be negligible and molecular emissions will account for effectively all of the observed signal. Under these circumstances, the signal may vary in appearance from a highly structured spectrum (as shown for CO in Figure 1) to a somewhat continuous one (as for CO<sub>2</sub> in Figure 1), depending on the density of individual spectral lines. In addition, if the atmosphere between the plume and the spectrometer has absorption features in the same spectral region (arising from the same or different molecular species as in the plume), some of the radiation emitted by the plume will be totally or partially absorbed before reaching the spectrometer. This is most clearly seen in the CO<sub>2</sub> spectrum of Figure 1 in which the center of the band from approximately 2320 cm<sup>-1</sup> to 2375 cm<sup>-1</sup> is strongly absorbed by CO<sub>2</sub> in the ambient atmosphere. A more subtle effect, and consequently not as clearly seen in this figure, is that caused by temperature gradients in the plume itself. If the periphery of the plume is cool, the gases in this region will tend to absorb the radiation arising from the hotter core, giving rise to an effect very similar in appearance to that of atmospheric absorption. In general, the same species will be present throughout the plume although in varying concentrations. Consequently, this "self-absorption" almost always will be present, although its magnitude will be strongly affected by the temperature and concentration gradients within the plume.

If, in addition to molecular species however, the plume does contain significant particulate matter, these particulates will give rise to scattering as well as "greybody" emissions. Both of these effects yield spectrally structureless radiation, which is very distinct from the molecular emissions discussed above. The presence of scattering or greybody emissions will generally be seen as a raising of the base-line (zero-line) on plots such as Figure 1, possibly with some loss in the intensity of the molecular features riding on this baseline. Because of their distinct appearance, however, these emissions can be easily identified and treated separately from the molecular effects.

The final potential contribution arises when the field of view of the instrument is larger than the plume or when the plume is particularly transparent. This contribution, that of "background" emissions, arises from all other radiating sources within the field of view of the instrument. Fortunately, this contribution may be accounted for by measuring the background radiance

directly, without the plume present, and then subtracting an appropriately weighted spectrum of these emissions from that obtained during plume measurement.

## GENERAL DISCUSSION OF FTIR MEASUREMENTS

### Characteristics of FTIR Devices

There are a number of passive infrared devices which conceivably could be used for collecting flare efficiency data. Among these are gas filter correlation spectrometers, radiometers, and filtered imagers. However, the device which is ideal at the current stage of development of the methodology is the Fourier Transform Infrared (FTIR) spectrometer.

The basis of FTIR operation is Fourier transform interferometry. Spectrometers based on this technique have two major sensitivity advantages over other types of spectral devices.\* The first arises from the fact that the entrance aperture can be made quite large compared to that of other spectrometer types, thus maximizing the energy gathering potential of the device. The second is inherent in the instrument's operational principle, that is: With an interferometer, the entire spectral region is observed simultaneously, whereas with a dispersive device (grating or prism), the wavelengths are scanned sequentially. The interferometer thus makes much more efficient use of available measurement time so that exceptional sensitivity can be provided without sacrificing the spectral resolution needed to isolate the individual gas species. A further advantage of FTIR results from its computer-based operation. With the system under computer control, the methodology used to yield concentrations and flare efficiency can be programmed on the dedicated instrument computer leading to an automated, remote flare monitoring system.

Physically, an FTIR spectrometer generally consists of an optical assembly, an infrared detector with associated amplifiers, and a computer-based data collection and processing system. The optical assembly usually contains a telescope to collect the energy and a modulator which frequency-encodes this energy in such a way that each wavelength is translated into an acoustic frequency. The amplitude of each acoustic frequency is then proportional to the magnitude of the energy at the corresponding wavelength. In essence, this process is equivalent to taking the mathematical Fourier transform of the incident energy.

The output of the interferometer is a waveform consisting of the summation of all acoustic frequencies present. This output, called an interferogram, is usually digitized and stored in a mini-computer for subsequent processing. When transformed, how-

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\* For further details, consult Bell, Robert John, Introductory Fourier Transform Spectroscopy, Academic Press, New York, (1972).

ever, this interferogram yields the full infrared spectrum of the source.

#### FTIR Operation

Optimizing the FTIR for flare monitoring requires consideration of a number of instrument characteristics, including:

- 1) spectral range,
- 2) spectral resolution,
- 3) data collection, and
- 4) field of view (including collection optics size).

The specific spectral range chosen is based on two considerations:

- 1) the need to include those regions containing the emission signatures of CO, CO<sub>2</sub> and the hydrocarbons, and
- 2) the desirability to maximize the signal-to-noise which, in part, can be enhanced by minimizing the spectral range.

Spectral range selection is accomplished by choosing a specific combination of detector and optics (each of which has particular spectral response characteristics) which, when combined, form the total instrument response function. For example, indium antimonide detectors respond from approximately 1.5 to 5.5 microns while mercury cadmium telluride detectors respond from approximately 2 to 14 microns, but with less sensitivity in the 2 to 5 micron region than that of indium antimonide. These characteristics, when used in conjunction with optical filters or various FTIR beamsplitters, may be used to isolate specific spectral regions enhancing the instrument signal-to-noise.

The spectral resolution required for a measurement is dictated by the inherent separation of the spectral lines which make up the infrared signatures of the species of interest as well as the signatures of possible interferants. Better (finer) resolution enhances the signature and, hence, the ease with which a specie may be identified, but it also decreases the signal-to-noise and requires a longer measurement time. This longer integration time may be undesirable if the flare is fluctuating or if temporal variations must be resolved.

The field of view and the size of the collection optics define the extent of the observation area. A large area is desirable, if filled with the flare source, to enhance the signal-to-noise ratio, but such an area may provide an undesirable temperature and concentration averaging if the source is not spatially homogeneous.

For a specific measurement scenario, all of these variables must be considered and carefully balanced in order to maximize the data usefulness. Because of the preliminary nature of the measurements presented here, full optimization was not possible. Improvements in sensitivity and data utility are therefore certainly possible.

## SECTION 4

### FIELD MEASUREMENTS OF A TYPICAL SMALL SCALE FLARE

A field measurements program was conducted at the John Zink Company, Tulsa, Oklahoma in order to collect infrared signatures necessary for the development and testing of flare remote sensing methodologies. This section discusses the procedures and instrumentation used for these measurements.

#### DESCRIPTION OF JOHN ZINK COMPANY FLARE

The flare used for the field measurements was a standard Model STF-S-8 steam flare manufactured by John Zink Company. During the test program, the flare burned propylene and nitrogen mixed to provide various heat contents. Steam injection was also used to provide soot suppression for some of the tests.

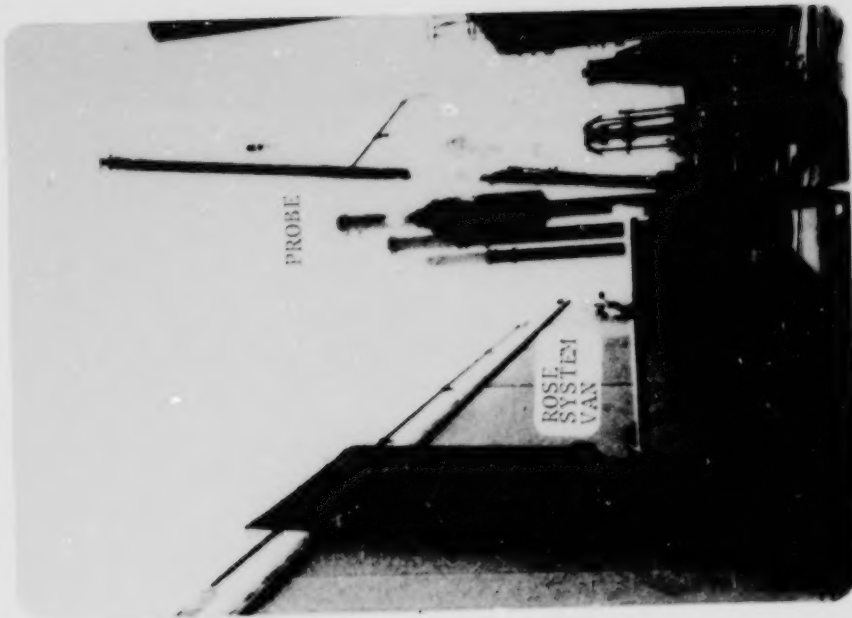
The tip of the test flare was 14 feet above the ground and 8 inches in diameter. Eight equally positioned steam injectors were mounted on the periphery at the top and the propylene/nitrogen mixture flowed up through the tubular body of the flare and ignited at the top by two natural gas pilots. The flame retention ring at the tip had an equivalent flow area of 27 square inches. Figure 4 shows two views of the flare including the extractive probe and the ROSE system van.

#### THE ROSE SYSTEM

The EPA ROSE (Remote Optical Sensing of Emissions) system was used for spectroscopic measurements at John Zink. This system is a van mounted, general purpose interferometer previously used for a variety of spectroscopic studies in the field. The essential elements of the ROSE system are:

- 1) a Nicolet Model 7199 Fourier transform interferometer with a f/5, 60 cm. Dahl -Kirkham telescope, and
- 2) a Nicolet Model 1180 digital computer and data acquisition system.

A schematic of the ROSE optical system is shown in Figure 5 while Table 2 provides a summary of the major parameters of the system as configured for the flare tests.



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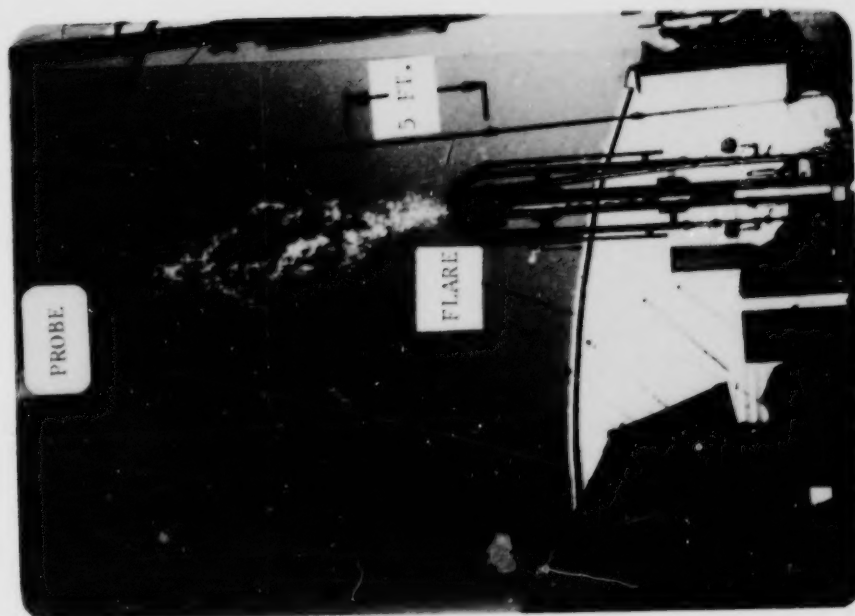


Figure 4. John Zink flare test from ROSE system position.

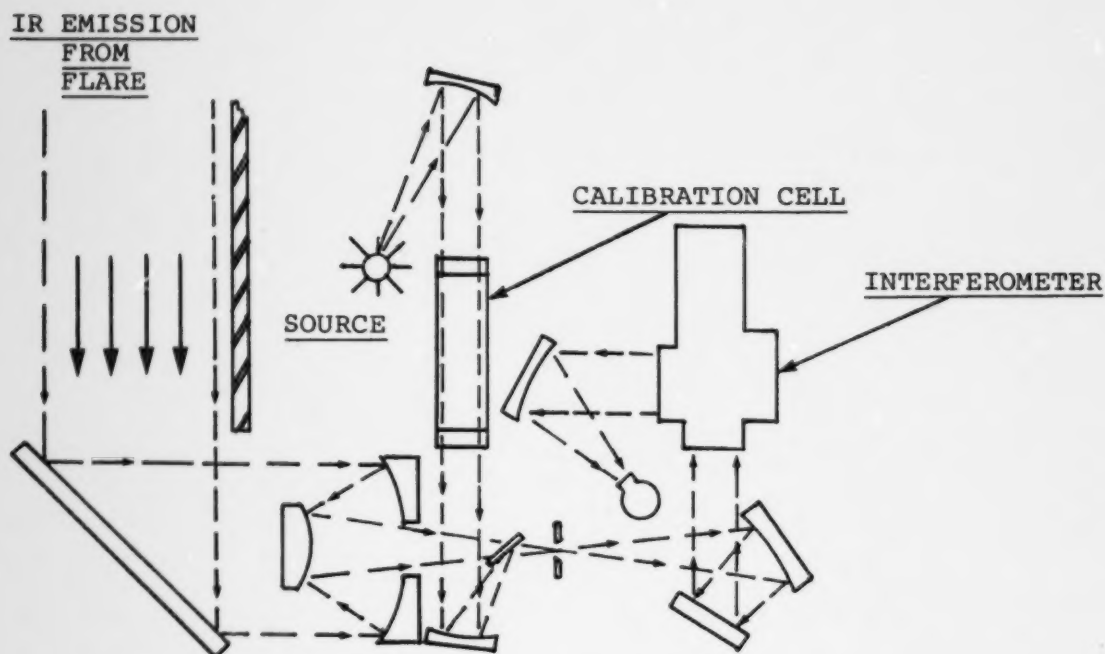


Figure 5. ROSE optical system.

TABLE 2. ROSE SYSTEM OPERATING PARAMETERS FOR FLARE MEASUREMENTS

| <u>Parameter</u>         | <u>Value</u>              |
|--------------------------|---------------------------|
| Spectral range           |                           |
| primary measurements     | 1800 to 2500 wave numbers |
| additional measurements  | 800 to 1800 wave numbers  |
| Spectral resolution      | 1/4 wave number           |
| Field of view (at flare) | 60 cm.                    |
| Observation times*       | 4, 40 or 200 sec.         |

\* Sample-to-sample variable

Although the ROSE system is capable of measuring over the entire spectral region from 600 to 6000 wavenumbers by simultaneously using two detectors, the system signal-to-noise ratio was maximized for the John Zink measurements by substituting a single indium-antimonide detector which covered the most important region from 1800 to 6000 wave numbers. A second mercury-cadmium-telluride detector was used for limited tests requiring longer wavelength coverage. Spectral resolution, another adjustable system parameter, was fixed at  $1/4$  wavenumber for these tests. This value was felt to be the best compromise between sensitivity which decreases with increasing (better) resolution and gas detectability which increases with increasing resolution.

The area observed by the system was dictated primarily by the 60 cm size of the receiver telescope since the acceptance angle of the telescope was less than 1 milliradian. Consequently, the sampled area was also fixed for all the measurements.

Included in the ROSE van is a 1 meter long multiple pass optical cell with a vacuum pump and high intensity light source. This cell is located adjacent to the interferometer and allows the same system to be used for collection of both flare data and absorption spectra of standard gases or independently collected air samples. Measurements made on the "calibration" gases discussed in Appendix A were made using this cell.

#### EXTRACTIVE PROBE

An extractive probe was used simultaneously with the ROSE system in order to obtain independent measurements of plume temperature as well as  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{SO}_2$ , and total hydrocarbon concentrations. As illustrated in Figure 4, the probe assembly was suspended from a crane so that the tip would be above the reaction zone (flame), in an area of assumed complete combustion. Guy wires and the crane were used to adjust the probe position.

A sample line conducted the samples to analysis instrumentation located in two separate Engineering Science trailers. Three basic types of samples were collected: (7)

- 1) "continuous" samples of  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NO}_x$  and  $\text{SO}_2$  recorded every 10 seconds with an instrumental response time of 20 seconds;
- 2) "instantaneous" samples for gas chromatographic analysis of individual hydrocarbon species, collected every 5 or 6 minutes with a 20 second sampling window; and
- 3) "integrated" samples collected into bags over time periods of 5 to 15 minutes and subsequently analyzed by gas chromatography.

The specific instrumentation used by Engineering Science is tabulated in Table 3. Note that the CO and CO<sub>2</sub> analysis is performed by an infrared technique as is the FTIR, although with some significant differences to be discussed later.

TABLE 3. INSTRUMENTS USED TO ANALYZE PROBE SAMPLES

| <u>Instrument</u>              | <u>Type</u>                            | <u>Constituent</u>  |
|--------------------------------|----------------------------------------|---------------------|
| Thermal Electron<br>(Model 10) | Chemiluminescence                      | NO <sub>x</sub>     |
| Horiba PIR 2000                | IR Absorption                          | CO, CO <sub>2</sub> |
| Teledyne 320 AX                | Electro "Catalyst"                     | O <sub>2</sub>      |
| Scott 116                      | Flame Ionization                       | THC                 |
| Carle 211                      | Gas Chromatograph/<br>Flame Ionization | HC Species          |
| Meloy SA 285                   | Flame Photometer                       | SO <sub>2</sub>     |

#### DATA COLLECTION

For the John Zink tests, the ROSE system was used in a passive emissions mode in order to view the 14 foot high flare over a slant path of approximately 60 feet. In this mode, the system collects spectra using the radiation emitted by the hot-gases in the flare plume. However, this data must be corrected for ambient radiation levels and calibrated in absolute radiance units before it can be analyzed to identify the species present or their concentrations. A full measurement sequence therefore consists of collecting several different types of data:

- 1) flare emissions data containing information on the combustion products,
- 2) background data quantifying the ambient radiation levels, and
- 3) calibration data defining inherent system response characteristics.

Procedures used for the collection of each of these types of data are given below, after which a comprehensive discussion is presented of the procedures required to combine these data sets into absolute, calibrated results.

## Flare Emissions

For the majority of the emission measurements, the FTIR field of view was positioned coincident with the extractive probe, typically several feet above the end of the combustion zone. This was the area estimated to be most representative of the final specie concentrations. However, FTIR data were also taken of sample areas 2, 6 and 16 feet above the flare tip as well as within the visible flame itself. The purpose of these latter measurements was to determine the change in specie concentrations with height and to substantiate the assumption that the optimum flare location for spectroscopic measurement of efficiency is above the combustion zone rather than within it.

During collection of flare emission data, the wind also caused the flame to move relative to the field-of-view of the interferometer. Since this could cause temporal fluctuations in the data adversely affecting the spectrum, several different "averaging" periods were used to insure collection of data under conditions minimizing these effects. The averaging period was varied by co-adding different numbers of individual spectra each of which required approximately 4 seconds to collect. For most runs, a single 4 second data collection was used followed by 40 second and 200 second averaging runs.

The wind bending of the flare also caused problems for the probe. To insure that the region being sampled was in the flow-field above the reaction zone, the probe had to be moved from run-to-run and frequently during a given run as well. Since the FTIR data was to be compared with that of the probe, if the probe was relocated, the steering mirror on the ROSE system was used to maintain the FTIR field-of-view coincident with it. In this way, common sampling areas were always being used by the two systems.

## Optical Backgrounds

"Background" data is required to establish the ambient radiation levels, specie concentrations, and atmospheric-constituent levels present at the measurement sight. The first two of these are necessary to correct the flare data for radiation sources or ambient gas emissions/absorptions within the system field-of-view. The last is required to quantify the propagation characteristics of the atmosphere between the flare and the ROSE system, allowing for interpretation of the observed spectrum. To collect these "background" data, emission scans identical to those taken on the flare itself were collected just before or just after a flare run using as much as possible the same fields-of-view. Since this data contained contributions from the sky or terrain behind the flare which would be obscured by the combustion plume during a test, ratios of the plume area to the field-of-view area were used to scale the "background" data for use in spectra generation. Additional information on local atmospheric propagation characteristics was also obtained by collecting emissions data while viewing the hot wall of the flare body slightly

below the tip. This effectively used the flare body as an infrared source allowing for observation of the intervening atmospheric species in absorption.

#### Calibration Data

The spectral features of the infrared spectrum identify the particular constituents present in the flare. The intensity of these features then dictate the concentrations of the species giving rise to the features. However, to quantify these concentrations, an absolute calibration of the instrument is essential, allowing for extraction of the actual wattage per unit solid angle per unit wavelength arising from the emitting gases. To achieve such an absolute calibration, additional "emissions" data are collected with the interferometer system, but here a "blackbody" source is used for which the total power output with wavelength and solid angle is a calculable quantity.

To collect data of this type for the ROSE system, a Barnes blackbody was used in conjunction with a 60 cm diameter Dahl-Kirkham transmitter/telescope. This combination, used at a distance of 59 feet from the van, supplied a radiation field of known intensity which filled the field-of-view of the ROSE system. Using data collected in this configuration, one could correct the data for instrumental effects and extract absolutely calibrated data.

#### Calibration of FTIR

The output of the FTIR, known as an interferogram, is not directly usable for analysis. Although this interferogram contains all the available spectral information, it must be Fourier transformed before it is recognizable as an infrared spectrum. Once this is done, the resultant spectrum then must be "background" corrected and calibrated before it can be used to extract specie concentrations or flare efficiencies. The procedures used to perform these tasks are outlined below in the form of five data reduction steps.

##### Step 1: Generate Low Resolution Spectra

A mathematical process known as a fast Fourier transform (FFT) was applied to all interferograms (flare emission, optical backgrounds and calibrations) to generate infrared spectra. Since a low resolution (2 wave numbers) FFT requires only a few seconds of computer time, whereas a high resolution (1/4 wave number) transform takes several minutes, the first step was to perform low resolution transforms on all of the collected data in order to provide hard copy spectra suitable for further data editing. Approximately 100 low resolution transforms were obtained and plotted in this way. It should be noted that these plots are adequate only for evaluation of the potential usefulness of each spectrum in subsequent flare efficiency analysis; the needs of the analysis can be completely satisfied only using full high resolution data.

## Step 2: Perform Data Quality Evaluation

The low resolution plots were reviewed and categorized as to relative value for further processing. The criteria used in this initial evaluation were: signal-to-noise ratio, the absence of signal saturation, and the indication of observable gas emissions. A further sorting was performed to create a matrix of spectra which would best represent the low, medium, and high propylene, steam, and nitrogen flow rates as well as the several spatial sampling positions. Background and calibration data appropriate to those specific flare spectra were also identified. The result of this editing process was the identification of 26 plume samples, 14 calibration samples, and 10 background data sets viable as candidates for full resolution FFT processing. The specific samples identified in this way are listed in Table 4 by both test number and local time.

TABLE 4. FLARE TEST PARAMETERS FOR FTIR SAMPLES (8)

| OMI Test No. | Test No. | Day  | Local Time | Sampling Point | Sample Time (sec.) | Propylene Flow (lbs/hr) | Nitrogen Flow (lbs/hr) | Steam Flow (lbs/hr) | Exit Velocity (ft/min) |
|--------------|----------|------|------------|----------------|--------------------|-------------------------|------------------------|---------------------|------------------------|
| 7            | 2        | 6/17 | 17:13:08   | (1)            | 400                | 3078                    | -                      | 1564                | 2475                   |
| 12           | 3        | 6/18 | 10:03:33   | 36             | 200                | 3027                    | -                      | 1355                | 2432                   |
| 76           | 4        | 6/22 | 21:45:30   | 47             | 4                  | 1875                    | -                      | -                   | 1509                   |
| 23           | 5        | 6/18 | 17:00:52   | 41             | 136                | 991                     | -                      | 1543                | 795                    |
| 25           | 5        | 6/18 | 17:14:06   | 35             | 400                | 991                     | -                      | 1543                | 795                    |
| 95           | 11a      | 6/24 | 07:32:13   | 41             | 4                  | 612                     | 2489                   | -                   | 3520                   |
| 124          | 16a      | 6/24 | 10:59:29   | 31             | 4                  | 329                     | 1182                   | -                   | 1907                   |
| 118          | 16b      | 6/24 | 11:03:24   | (2)            | 40                 | 313                     | 897                    | -                   | 1344                   |
| 119          | 16b      | 6/24 | 11:07:38   | (2)            | 200                | 313                     | 897                    | -                   | 1344                   |
| 42           | 17       | 6/21 | 12:49:55   | 25             | 40                 | 162                     | -                      | 150                 | 131                    |
| 44           | 17       | 6/21 | 12:56:54   | 25             | 4                  | 162                     | -                      | 150                 | 131                    |
| 58           | 23       | 6/21 | 19:19:30   | 29             | 4                  | 0.451                   | 2.13                   | -                   | 2.63                   |
| 50           | 50       | 6/21 | 14:10:00   | 25             | 56                 | 162                     | -                      | 498                 | 130                    |
| 54           | 51       | 6/21 | 18:05:23   | 29             | 4                  | 305                     | 1222                   | 256                 | 1733                   |
| 61           | 52       | 6/21 | 19:59:10   | 19             | 200                | 0.452                   | 2.14                   | 201                 | 2.96                   |
| 68           | 53       | 6/22 | 16:26:02   | 18             | 40                 | 0.226                   | 1.41                   | 201                 | 1.90                   |
| 71           | 54a      | 6/22 | 17:19:59   | 18             | 40                 | 0.226                   | 1.41                   | -                   | 1.90                   |
| 73           | 54b      | 6/22 | 17:30:32   | 19             | 200                | 0.226                   | 1.41                   | -                   | 1.90                   |
| 88           | 55       | 6/23 | 14:04:34   | 26             | 200                | 164                     | -                      | 1125                | 132                    |
| 89           | 55       | 6/23 | 14:06:49   | 26             | 200                | 164                     | -                      | 1125                | 132                    |
| 90           | 56       | 6/23 | 14:49:38   | 25             | 4                  | 163                     | -                      | 562                 | 131                    |
| 109          | 57a      | 6/24 | 09:21:06   | 42             | 40                 | 629                     | 2663                   | 497                 | 3749                   |
| 129          | 59a      | 6/24 | 21:50:03   | (3)            | 200                | 345                     | 2361                   | -                   | 3152                   |
| 132          | 59b      | 6/24 | 21:55:16   | 37             | 200                | 350                     | 1942                   | -                   | 2645                   |
| 137          | 60d      | 6/24 | 23:13:15   | (4)            | 4                  | 212                     | 1325                   | -                   | 1781                   |
| 139          | 60d      | 6/24 | 23:24:38   | (5)            | 4                  | 212                     | 1325                   | -                   | 1781                   |

NOTE: Sample area for spectrometer if not at probe:

- (1) near exit
- (2) 6 ft. above flare tip
- (3) top of flame
- (4) top of flame
- (5) 2 ft. above flare tip

## Step 3: Generate Full Resolution Spectra

High resolution (1/4 wavenumber ) spectra were then generated for the data indicated in Table 4. Each resulting spectrum was then archived on disk for permanent storage and for subsequent analysis.

#### Step 4: Spectrometer Calibration

The spectrometer calibration relates the spectral amplitudes in the spectra to the intensity of the infrared energy received by the system at each wavenumber. In general:

$$S = R * P \quad (12)$$

where:

S = the observed amplitude

R = the response of the total FTIR system, and

P = the power received by the system.

If the system is used to collect emissions data while viewing a blackbody calibration source, the signal received will be a combination of the blackbody energy (BB), radiation arising from backgrounds within the field-of-view (BKG), and emissions arising from the ambient temperature optics of the interferometer itself (SPEC). Consequently,

$$S[BB + BKG + SPEC] = R * [P(BB) + P(BKG) + P(SPEC)] \quad (13)$$

By independently measuring the background signal, which also contains the spectrometer self-emission signals, one obtains:

$$S[BKG + SPEC] = R * [P(BKG) + P(SPEC)] \quad (14)$$

If this is subtracted from Equation (13), the instrument response may be evaluated as:

$$R = S(BB)/P(BB) \quad (15)$$

Since P(BB), the power arising from the blackbody, is defined by the Planck radiation function, a measurement of the "background" signal and the "observed" blackbody signal completely (Equation (13)) defines the system response.

### Step 5: Calibration of Observed Flare Data

Data collected during a flare test has the same form as that of Equation (13). That is:

$$S(\text{Flare} + \text{BKG} + \text{SPEC}) = R * [P(\text{Flare}) + P(\text{BKG}) + P(\text{SPEC})] \quad (16)$$

If an independent measurement of background emissions is taken for the flare measurement configuration and this is subtracted from the raw data, the calibration factor can be applied to give  $P(\text{flare})$  directly. That is:

$$P(\text{Flare}) = \frac{1}{R} [S(\text{Flare} + \text{BKG} + \text{SPEC}) - S(\text{BKG} + \text{SPEC})] \quad (17)$$

This may then be put into radiance or irradiance units by dividing by the appropriate receiver areas or solid angles.

### Flare Tests Observed

Table 5 provides an indication of the quantity of data collected for each of the basic data categories discussed above.

TABLE 5. MEASUREMENTS AT JOHN ZINK COMPANY, 17-24 JUNE 1982

|                                              |      |
|----------------------------------------------|------|
| ● Flare Tests Observed (All Steam Assisted): | 21   |
| ● Flare Emission Samples (IR Spectra)        | : 94 |
| ● Useful Samples For Analysis                | : 60 |
| ● Optical Backgrounds                        | : 14 |
| ● Calibration Gas Samples Analyzed           | : 5  |

Data from 18 of the 21 flare tests were processed to the form needed for review and analysis. Table 4 compiles propylene, nitrogen, and steam flow rates for these 18 tests, along with the aim points and sample times used.

## SECTION 5

### DEVELOPMENT OF FLARE EFFICIENCY CALCULATION METHODOLOGY

#### GENERAL APPROACH

Evaluation of flare efficiencies requires measurement of gas concentrations in the plume above the reaction zone. Remote infrared methods can be used to determine these concentrations, but auxiliary information is required because these methods yield an integrated absorption or emission value representative of the total line of sight through the plume. If the plume is homogeneous and isothermal, this would not represent a major problem since concentrations could be simply backed out of the IR measurements using the plume dimensions. In reality, however, the plume is neither homogeneous nor isothermal so that both the gas concentrations and the temperature vary throughout. This means, of course, that there is no single temperature or single concentration which is representative of the plume. Instead, one must determine a distribution for these parameters or fit such a distribution to the observed data. Once this distribution is evaluated, however, one may determine either global or local characteristics for the plume, including combustion efficiencies.

In general, the approach developed in the present study was to assume a Gaussian distribution for both temperature and gaseous concentrations and to fit the parameters of this distribution to the observed data. As shown in Figure 6, the first step in doing this was to determine an effective or peak temperature for the distribution. This was accomplished in two ways: 1) by extracting parameters from the observed carbon monoxide emission band envelope, and 2) by fitting calculated carbon dioxide spectra to that observed. Once a temperature was determined, it was then used in a second iterative process to determine individual molecular concentrations. These were again evaluated by fitting calculated CO and CO<sub>2</sub> emission spectra to observed data. Given these concentrations, an approximate efficiency for the flare could then be computed. Details of the specific steps and procedures used in these processes are elaborated on below.

#### SPECIFIC PROCEDURE USED

The specific analytical procedures developed for reduction of flare data are outlined in Figure 7. Here, it is assumed that one begins with calibrated field data as discussed in Section 4. Using this data, temperatures and concentrations are evaluated

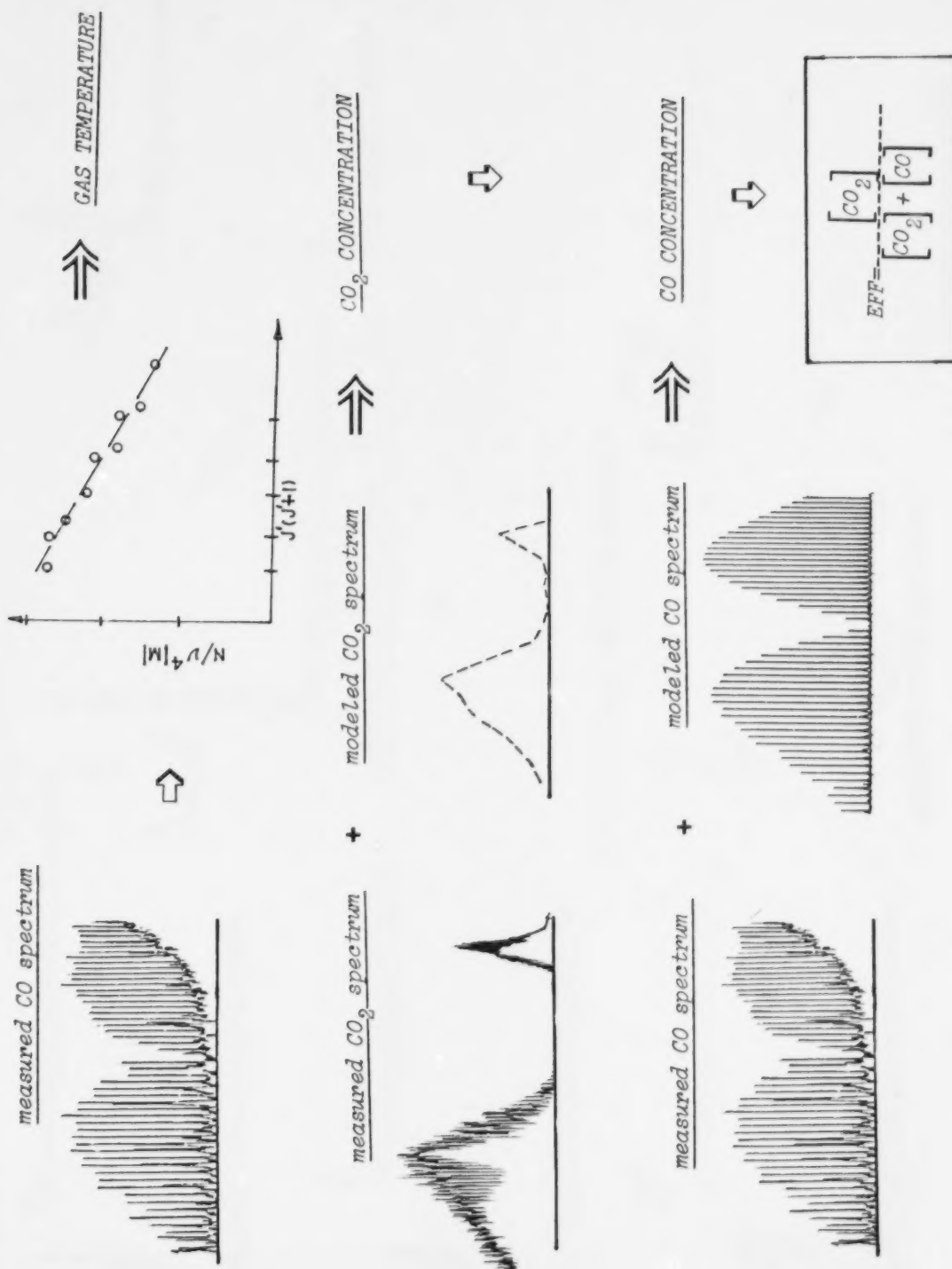


Figure 6. Flare monitoring scheme.

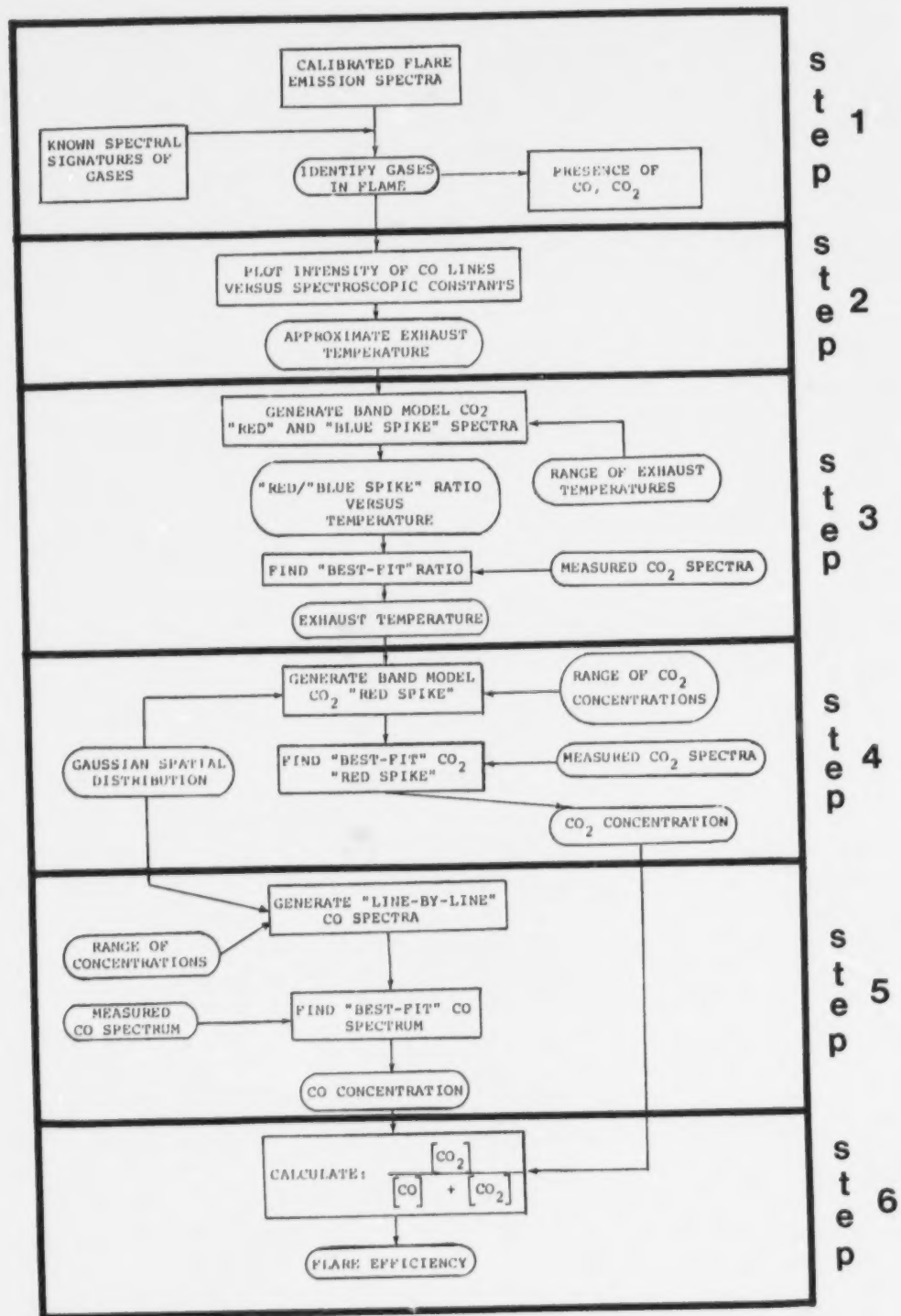


Figure 7. Analysis procedure developed for flare efficiency evaluation.

using the six-step procedure shown. In the subsections which follow, the individual steps in the procedure are discussed in detail.

### Step 1

The first step is to examine the spectral data looking at empirical and theoretical line positions of the several gases of interest to determine the species which are present in sufficient concentrations to yield usable signatures. With carbon dioxide, for example, the process is straightforward since there is a strong band (the  $\nu_3$  fundamental) in the region from 4 to 5 microns (2000 to 2500 wavenumbers) which has been well characterized in the past. Similar bands exist for all the major species.

### Step 2

After locating the major molecular bands of interest, the second step is to determine an initial value for the exhaust temperature. This is done using the band envelope of the CO fundamental band between 2000 and 2140 wavenumbers by making a semi-logarithmic plot of

$$\frac{N_v}{v^4 |m|} \text{ versus } J' (J' + 1) \quad (18)$$

where:  $N_v$  = the radiance of a given CO line

$v$  = wavenumber of that line

$J'$  = the quantum number of the initial state of the transition, and

$|m| = J' + 1$  (for the P branch used).

It can be shown that the slope of this plot is given by:(9)

$$\frac{B' hc}{kT} \quad (19)$$

where:  $B'$  = the spectroscopic rotational constant for the molecule under observation

$h$  = Planck's constant

$c$  = the speed of light

$k$  = Boltzmann's constant, and

$T$  = the desired temperature (Kelvin).

### Step 3

The initial temperature estimate is then used as a starting point for the generation of a matrix of computer-synthesized, low resolution,  $\text{CO}_2$  spectra used to evaluate a refined plume temperature. The  $\text{CO}_2$  calculations performed here used a band model code called ATLES (10) to produce a set of low resolution spectra in the so-called "red" and "blue-spike" regions of the  $\nu_3$ -fundamental band. As shown in Figure 8, the "red spike" extends from approximately 2200 to 2325 wavenumbers while the "blue spike" extends from 2375 to 2400 wavenumbers. These "spikes" are caused by  $\text{CO}_2$  atmospheric absorption which absorbs the center of the  $\text{CO}_2$  plume emissions before they reach the interferometer, leaving two "spikes" in the wings of the band.

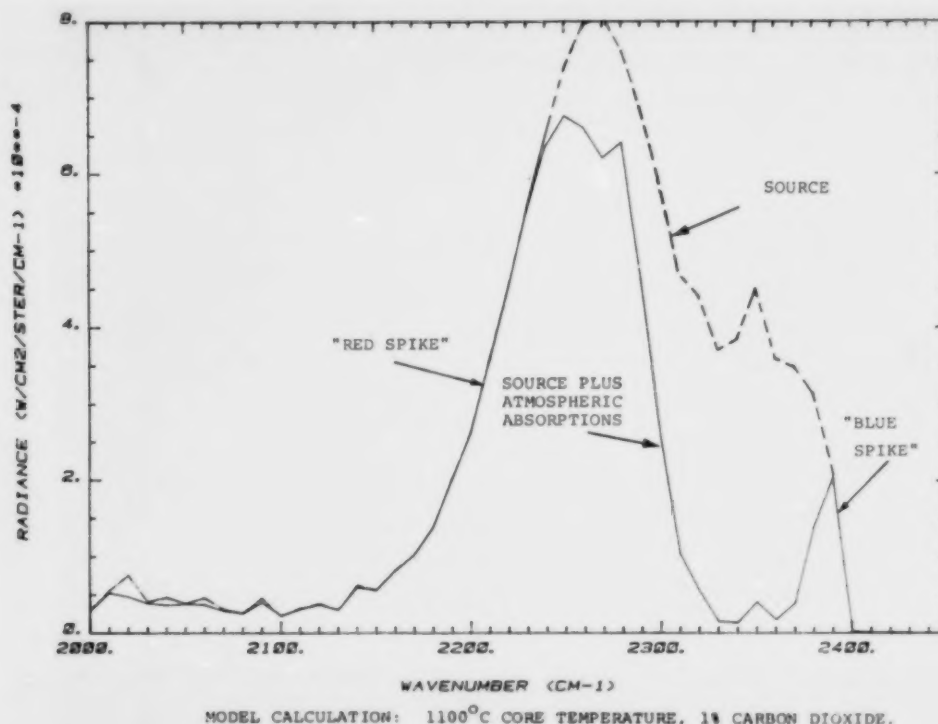


Figure 8. Creation of "red" and "blue" spikes of  $\text{CO}_2$ .

Since the flare plume is not homogeneous, calculation of these infrared emissions requires some measured or assumed spatial distribution for both the temperature and specie concentrations in the plume. Without any measured values for this distribution, a Gaussian profile such as that shown in Figure 9 was assumed for the present analysis. To test the sensitivity of the results to the profile chosen, a comparison was made between two profiles which had a factor of two difference in the speed with which their core values drop to ambient (roll-off). As

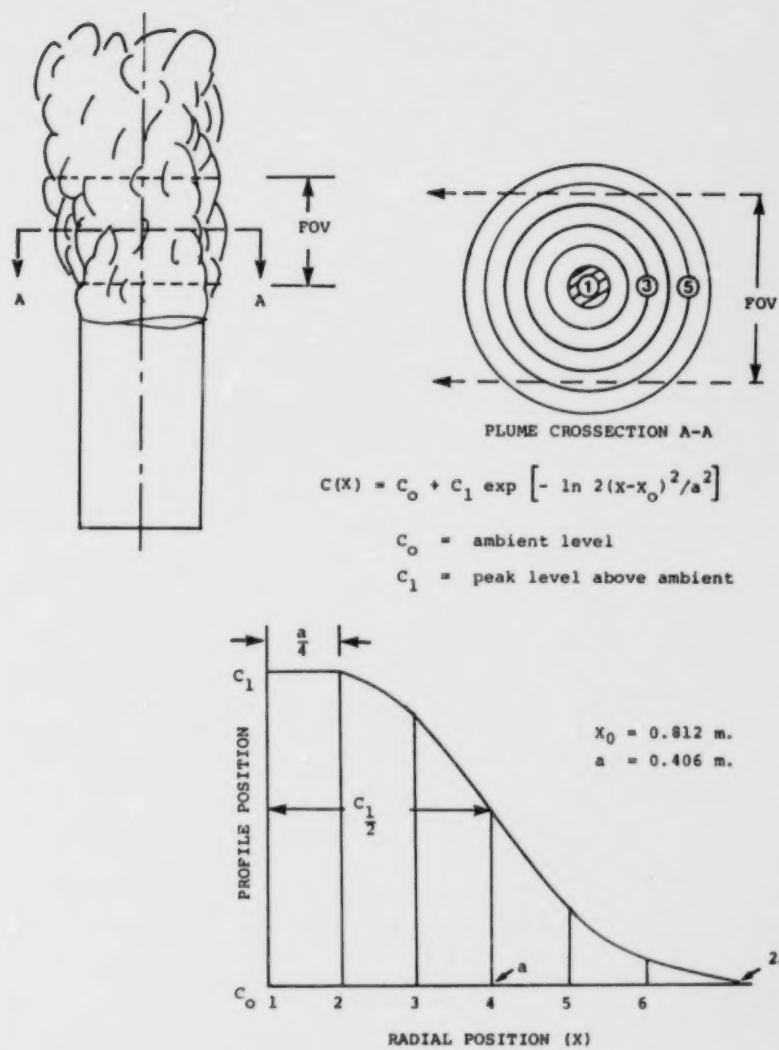


Figure 9. Gaussian spatial distribution.

indicated in Figure 10, the band model calculations were not significantly affected by this roll-off when the core temperature was held constant.

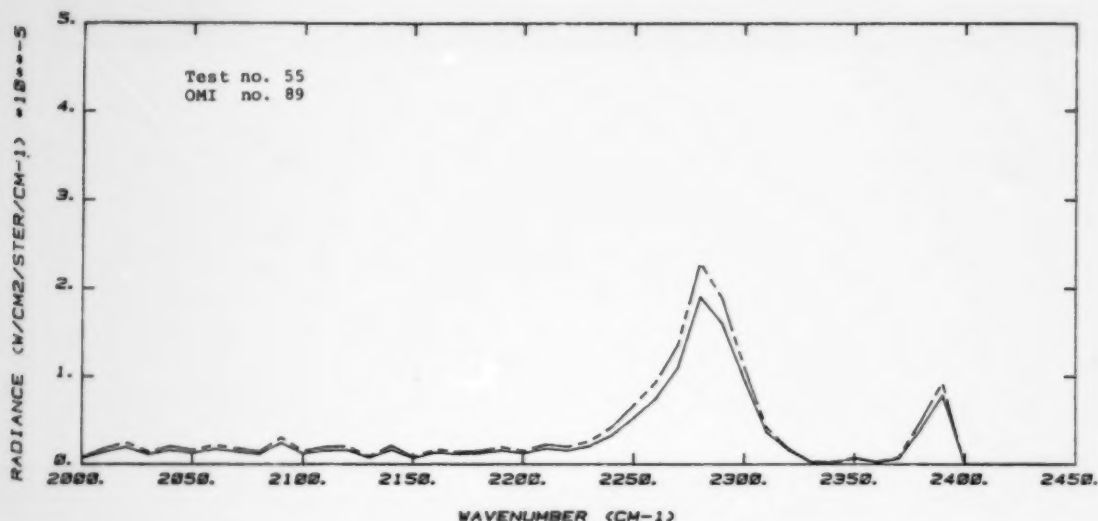


Figure 10. Radiance variations caused by altering Gaussian profile roll-off (lower curve rolls off twice as rapidly as upper).

It was observed, however, that the ratio of the peak intensities of the "red" to "blue" spikes is: 1) a strong function of peak temperature, as illustrated in Figure 11, and 2) independent of the concentration, as indicated in Figure 12. Consequently, the next step in the analysis procedure is to match computer-generated CO<sub>2</sub> spectra to the measured spectrum for a given test using the ratio of the amplitudes of the "red" and "blue" spikes to obtain a refined temperature estimate. This refined temperature is then used in the next step of the process to determine CO<sub>2</sub> concentrations.

#### Step 4

To determine CO<sub>2</sub> concentrations, the ATLES code is again used to produce a set of comparison spectra but, in this case, concentration is varied instead of temperature. Examples given in Figure 13 illustrate the uniform intensity increase of both the "red" and "blue" spikes with concentration. Given the nearly continuous absorption of the "red spike", however, it is used exclusively for determining a best-fit match with the measured CO<sub>2</sub> spectra because its peak intensity is relatively insensitive to instrumental resolution. Once a best-fit is found, the CO<sub>2</sub> concentration follows.

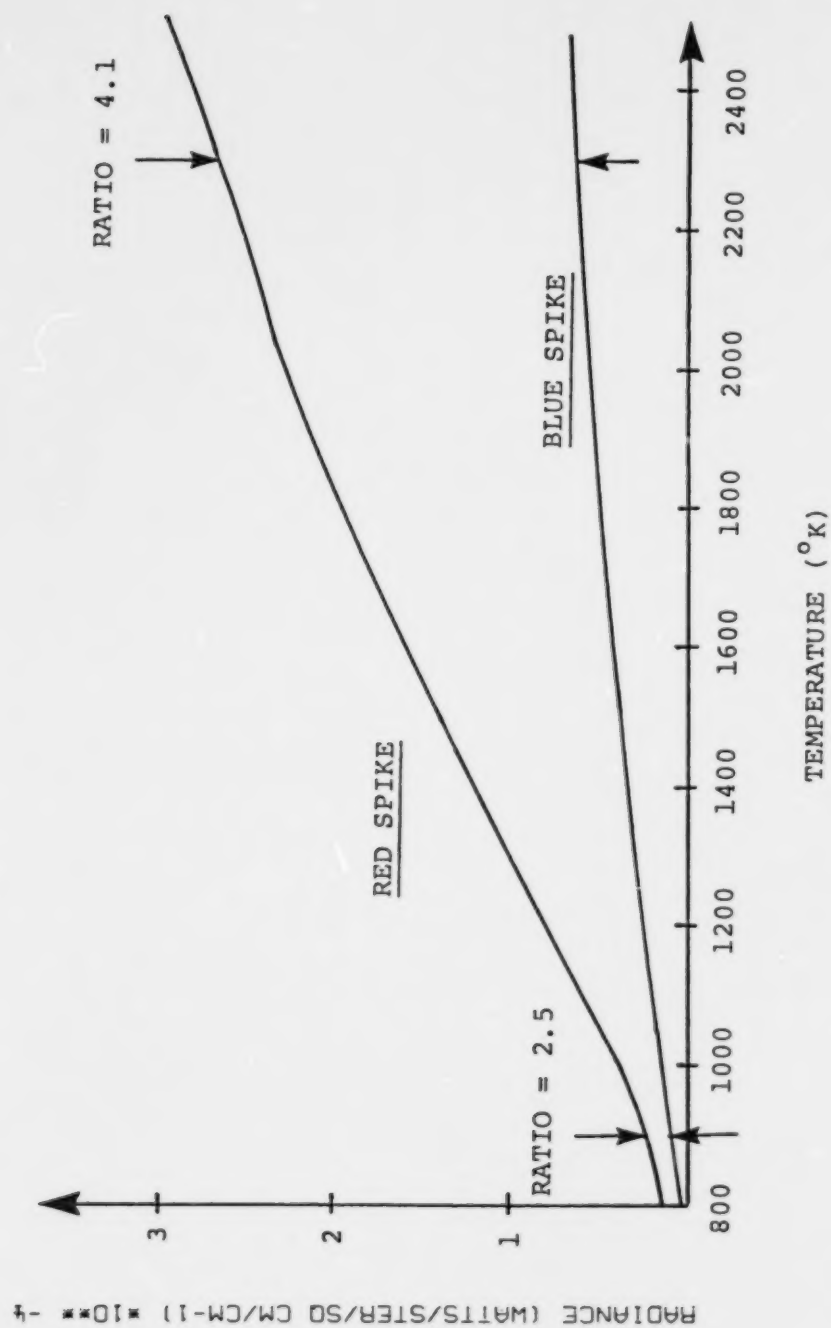


Figure 11. "Red" and "blue" spike intensities versus temperature.

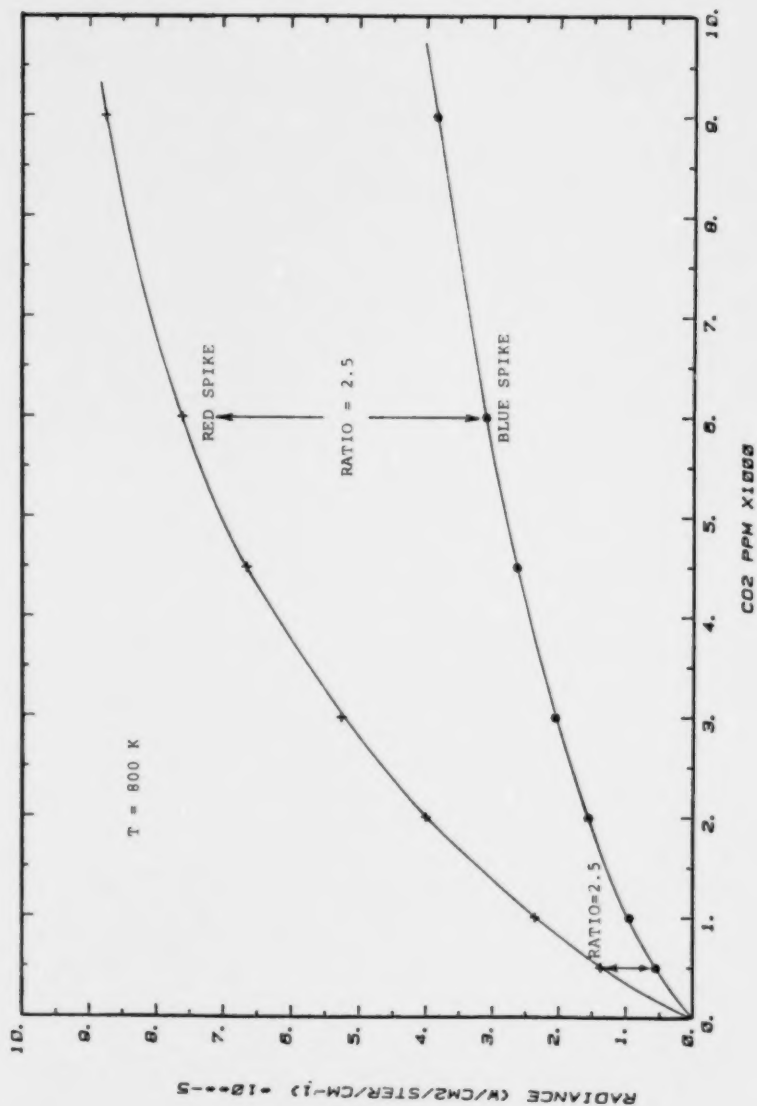


Figure 12. Variation in peak "red" spike and "blue" spike radiance with  $\text{CO}_2$  concentration at 800K.

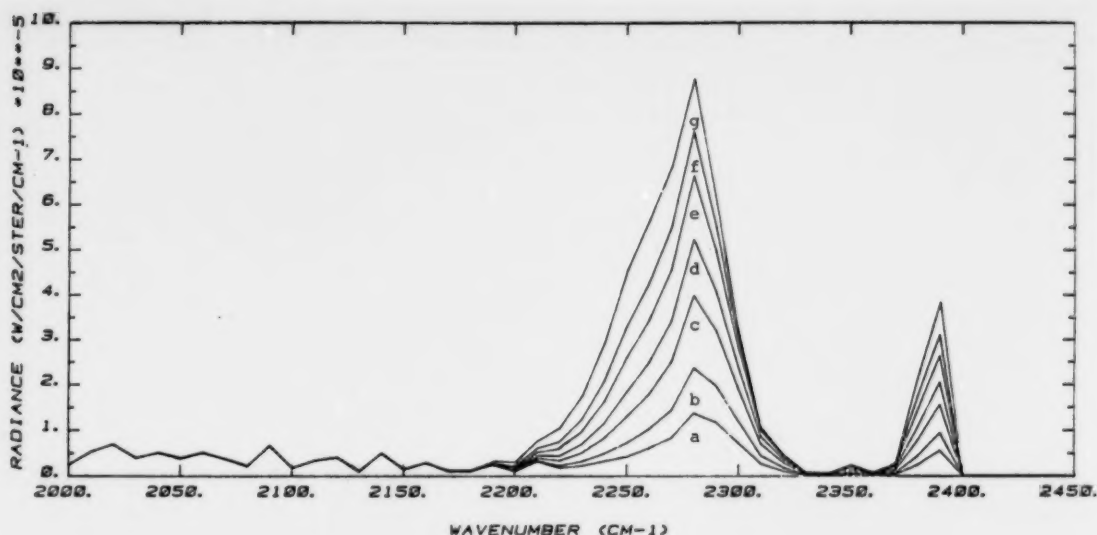


Figure 13. Families of curves for a flare temperature of 800K and concentrations of: a) 500, b) 1600, c) 2000, d) 3000, e) 4500, f) 6000, and g) 9000 ppm of CO<sub>2</sub>.

#### Step 5

To evaluate carbon monoxide concentrations in the plume, a similar "best-fit" procedure is used. Here, however, a high resolution comparison is necessary because the CO emissions arise from relatively isolated emission "lines," as shown in Figure 14, instead of continuous "bands" as in the CO<sub>2</sub> red spike. Even though the resolution required is different, the rest of the fitting procedure is essentially the same as that used for the CO<sub>2</sub>. The temperature and specie distributions determined from the CO<sub>2</sub> fits are used directly in the CO calculations. The CO concentration is then varied to find a best match to observed data.

To perform the CO spectrum calculations, an algorithm called FASCOD1 is used. This code effectively computes the contributions of each of the individual CO lines and then combines them into a single spectrum. The code has been extensively verified and has several characteristics rendering it well-suited to this particular task:

- 1) It computes the plume radiance as well as the transmittance of the intervening atmosphere and does so at a resolution high compared to typical instrumental capabilities;
- 2) it assumes local thermodynamic equilibrium characterized by temperature and pressure (equivalent to concentration); and

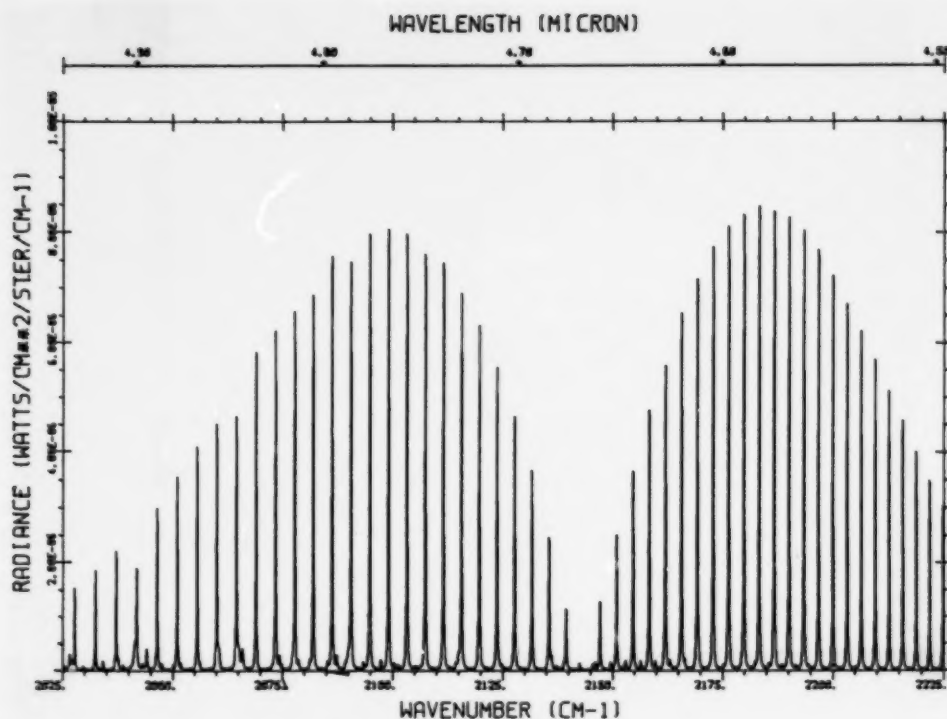


Figure 14. Predicted CO spectrum.

- 3) it allows for inclusion of an instrument scanning function so that the resolution of the calculations can be matched to that of the measurements optimizing spectra comparisons.

It should be noted that there is some potential for emission line interference in the CO region due to water vapor in the plume or the intervening atmosphere. To minimize the impact of this interference, the calculation is performed for some 50 lines in both the P and R branches. A "best-fit" match to all the lines is then used to evaluate the CO concentration for that test.

#### Step 6

The final step in the data analysis process is to calculate flare efficiency from Equation 2:

$$EFF \approx \frac{[CO_2]}{[CO] + [CO_2]} \quad (20)$$

The validity of this relationship at high efficiency levels is indicated in Figure 15. The data plotted in this figure are the results of the continuous extractive probe sampling data for

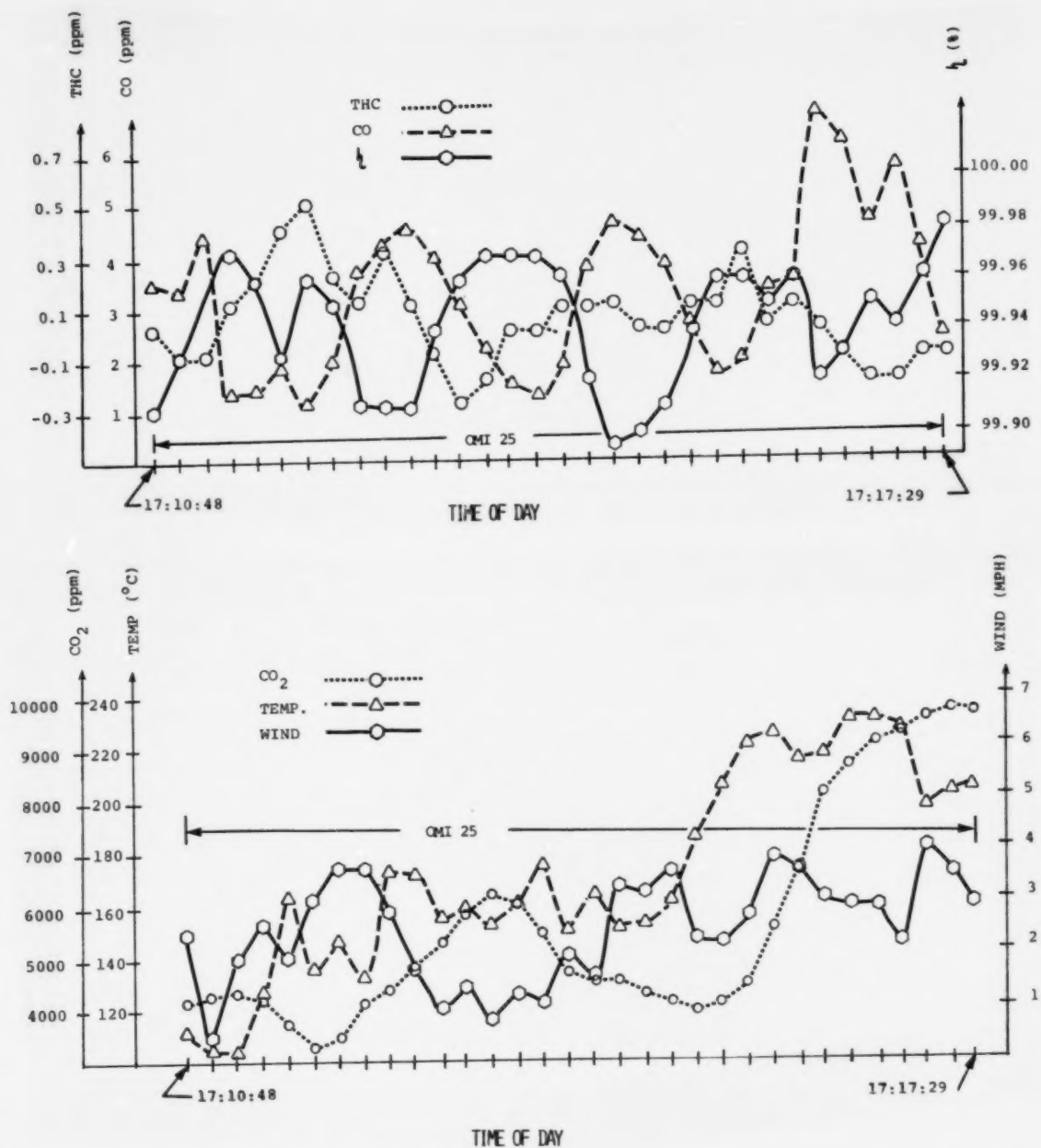


Figure 15a. Continuous probe sampling results - test 5.

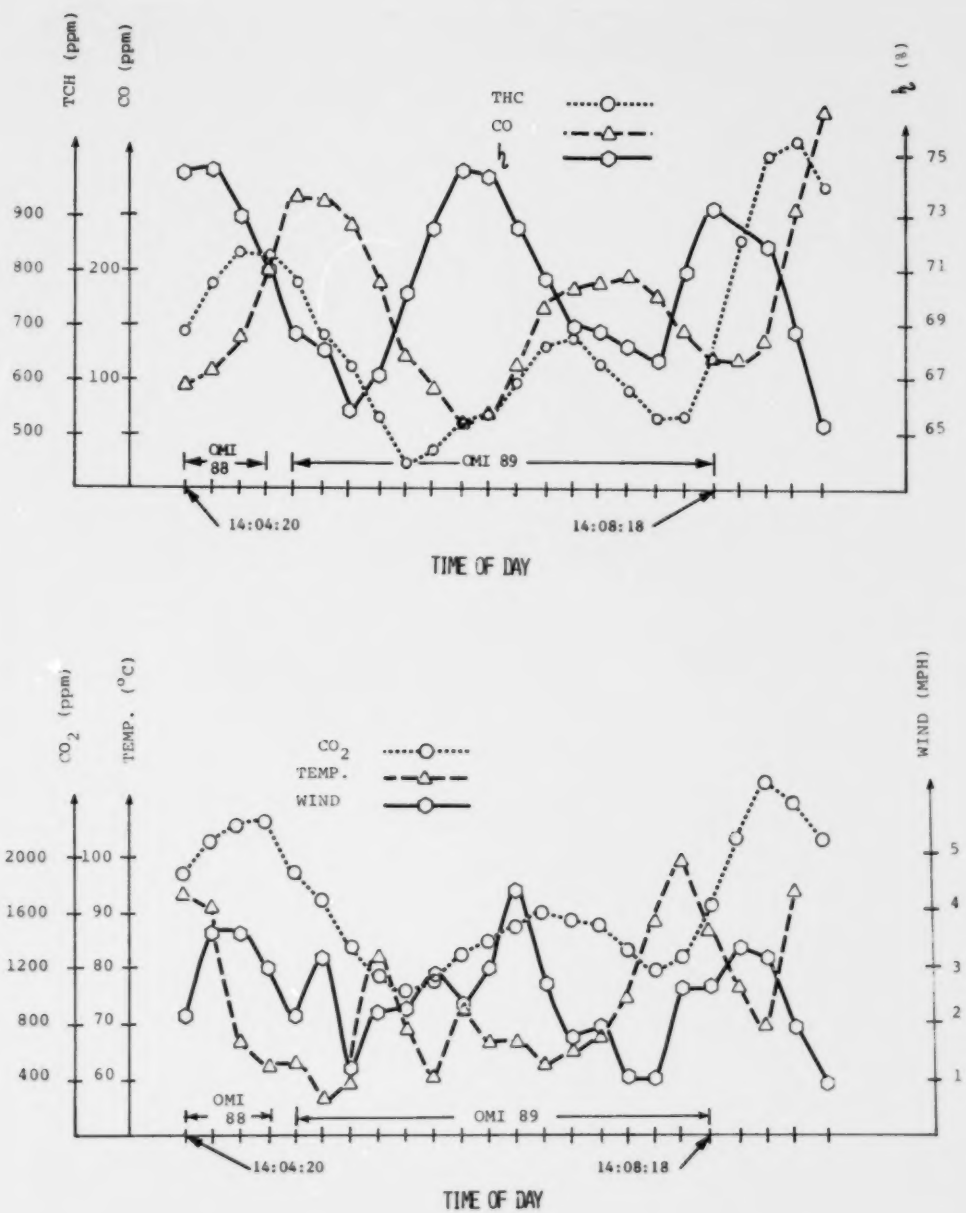


Figure 15b. Continuous probe sampling - test 55.

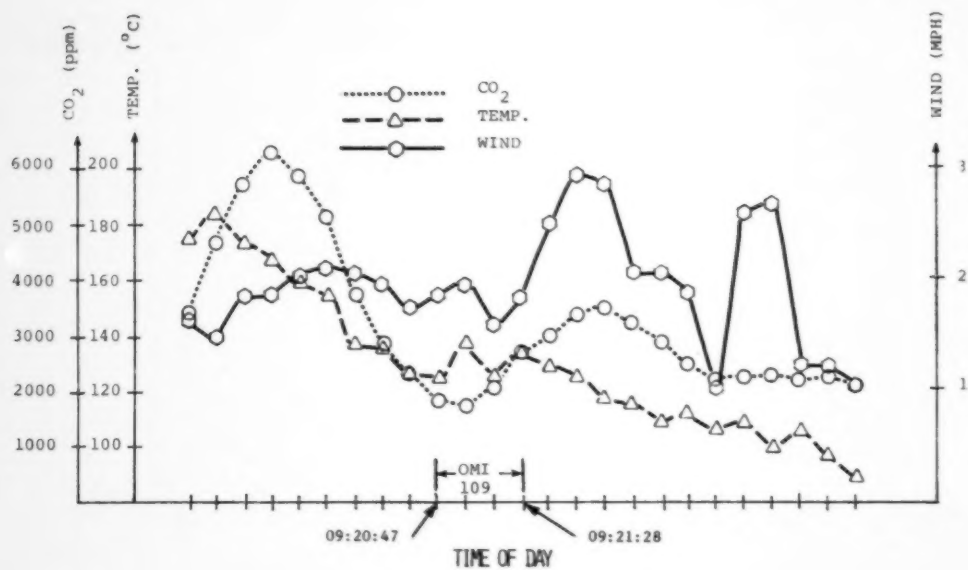
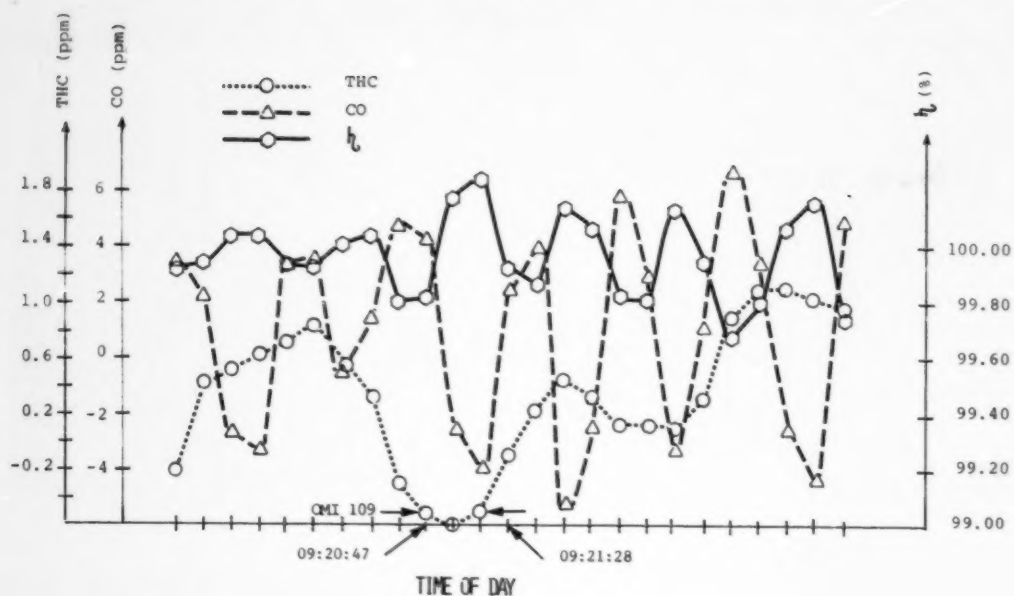


Figure 15c. Continuous probe sampling results - test 57.

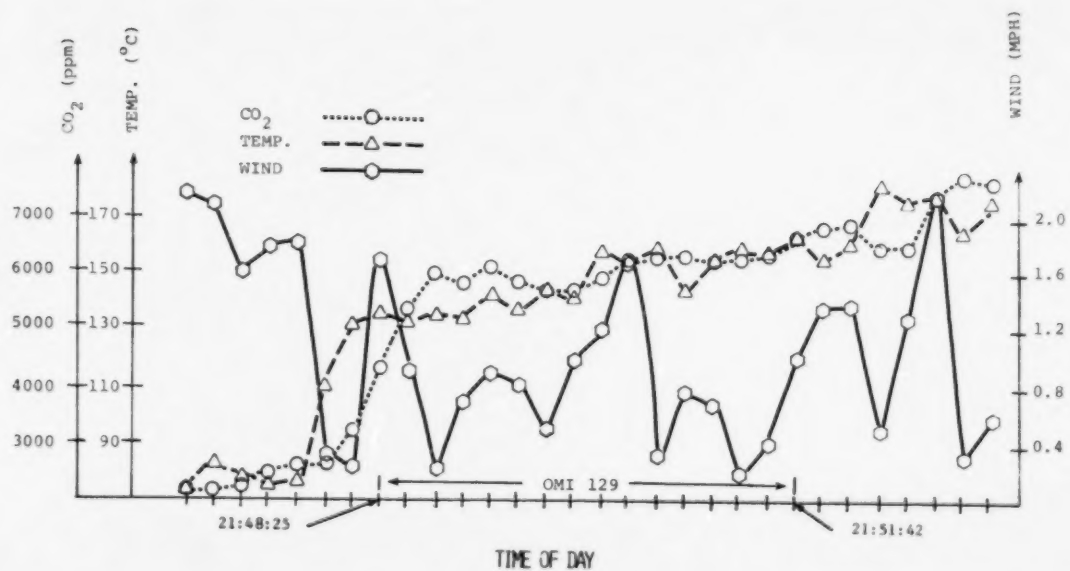
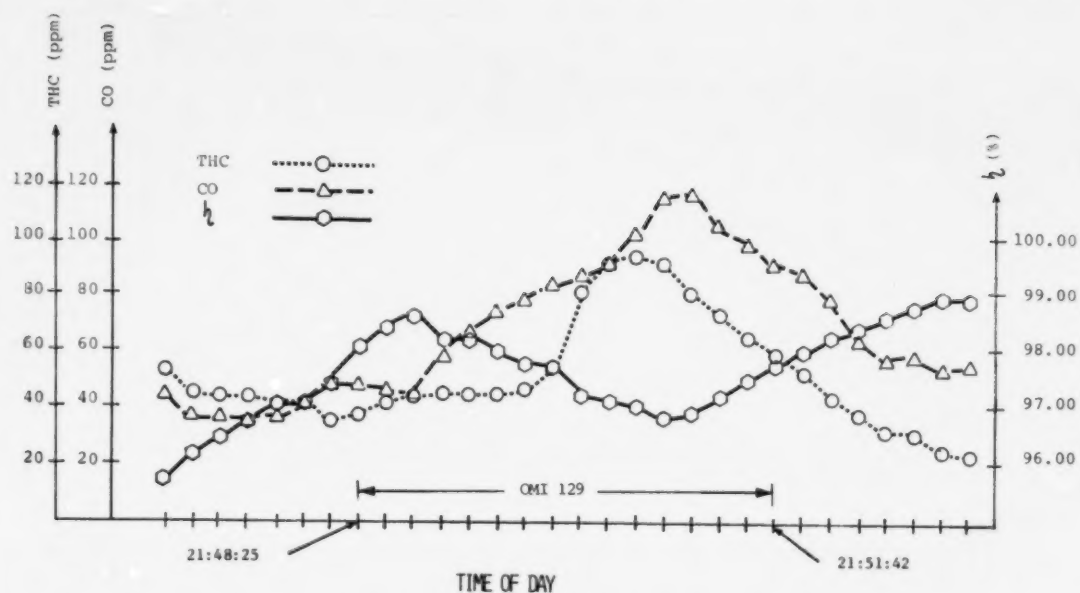


Figure 15d. Continuous probe sampling results - test 59.

CO, CO<sub>2</sub> and THC as collected by Engineering Science (12). The efficiency shown is that calculated from Equation 1 as:

$$EFF \equiv \frac{[CO_2]}{[CO_2] + [CO] + [THC] + [Soot]} \quad (21)$$

The strong inverse correlation observed in this figure between efficiency and CO concentration demonstrates that the approximate efficiency formula of Equation 2 is valid at high efficiency values. This appears to be the case because the total hydrocarbon concentration drops more rapidly than that of CO as efficiency increases so that, at high efficiency, CO concentration becomes the driving parameter.

#### CONCENTRATION CALCULATIONS FOR FOUR OBSERVED FIELD TESTS

The procedure outlined above was applied to the four flare tests listed in Table 6. The selection of these specific samples was based on:

- a) the observed signal-to-noise ratio of the data,
- b) the desire for representative examples of both high and low efficiency cases, and
- c) the desire to include sample areas both coincident with the probe and within the flame itself.

TABLE 6. FLARE TESTS FOR CONCENTRATION CALCULATION

| Test No.          | OMI No. | Height (ft.) | Time (sec.) | Efficiency(1)<br>(%) |
|-------------------|---------|--------------|-------------|----------------------|
| 55                | 89      | 26           | 200         | 69.7                 |
| 59 <sup>(2)</sup> | 129     | --           | 200         | 97.7                 |
| 50                | 50      | 25           | 56          | 99.1                 |
| 53                | 68      | 18           | 40          | 99.0                 |

Note (1): Average combustion efficiency from extractive probe measurements over same time interval as FTIR measurements (13)

(2): Sample area included flame

Figures 16 through 20 are the flare emission spectra which provided the input to the calculational procedures. Clearly observed in all spectra is the  $\text{CO}_2$  band appearing as red and blue spikes near  $2250 \text{ cm}^{-1}$  and  $2375 \text{ cm}^{-1}$ , respectively. Carbon monoxide is seen only in the low efficiency test (Test 55 of Figure 18) and in Test 59 (Figure 19), for which data were taken within the combustion zone itself. Superimposed on all the data are the best-fit computer-generated spectra derived using the procedures discussed above.

It should be noted that the obvious discrepancies observed between  $2200$  to  $2250 \text{ cm}^{-1}$  in the  $\text{CO}_2$  red spike region are attributable to deficiencies in the data base used by the ATLES code. These deficiencies are such that at higher temperatures ( $T > 900 \text{ K}$ ), one would expect the calculations to underpredict the wings of the band (as seen in Figures 16, 17 and 19) while agreeing well at lower temperatures (e.g., Figure 18).

The plots of relative CO intensities used for initial temperature estimates in Tests 55 and 59 are shown in Figure 20. The final temperature and concentration values calculated for all four tests are shown in Table 7.

TABLE 7. FLARE TEST TEMPERATURES AND CONCENTRATION (FTIR)

| Test No. | OMI No. | Temp. ( $^{\circ}\text{K}$ ) | $\text{CO}_2$ (ppm) | CO (ppm) | EFF. (%) |
|----------|---------|------------------------------|---------------------|----------|----------|
| 55       | 89      | 683                          | 1800                | 155      | 92.07    |
| *59      | 129     | 2500                         | 6000                | 1350     | >81.63   |
| 50       | 50      | 920                          | >6000               | <20      | >99.67   |
| 53       | 68      | 1400                         | 2900                | ~27      | 99.08    |

\*FTIR sample area 6 feet from flare tip within visible flame.

For comparison, the extractive probe results for these same tests are given in Table 8. Since the FTIR integrates over a large volume while the probe extracts samples at a point, one would expect differences to be inherent in the two results. Of the two data types, however, FTIR gives the more "global" result since it represents an average over the total cross-section of the plume, not just at a point within it.

#### DETECTION LIMITS

There are a number of factors in the measurement of flare efficiency by FTIR which have a potential impact on its accuracy. These include:

- 1) temporal fluctuations in the flare,

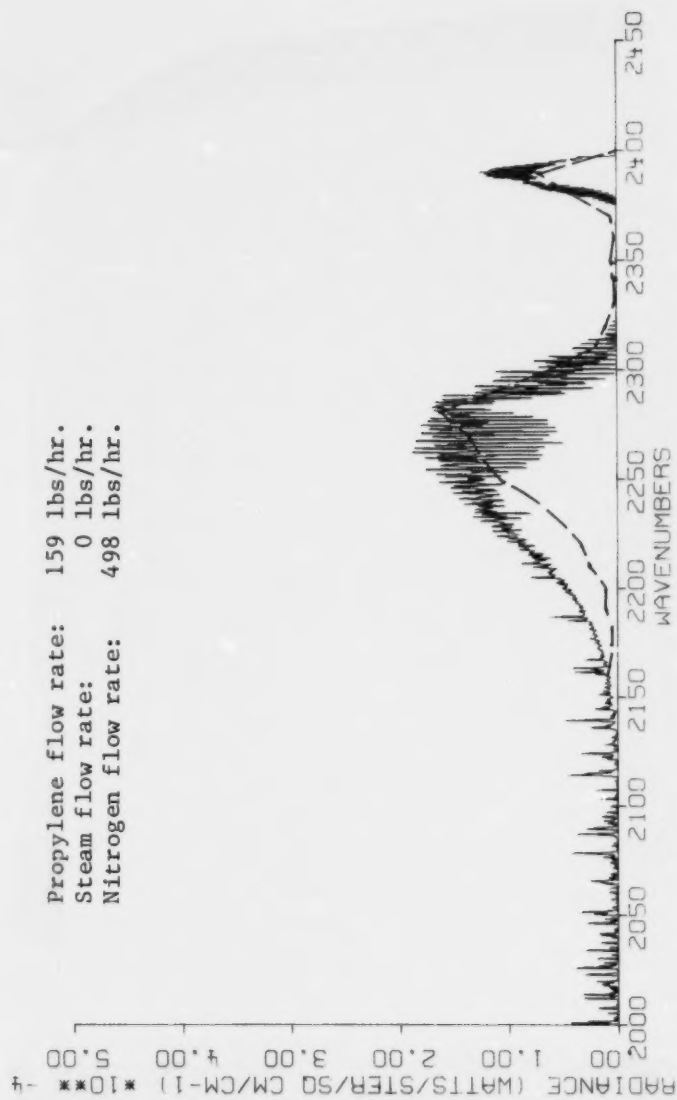


Figure 16. Observed and calculated flare radiances for test 50.  
 Deduced temperature = 920K with 6000 ppm CO<sub>2</sub>.

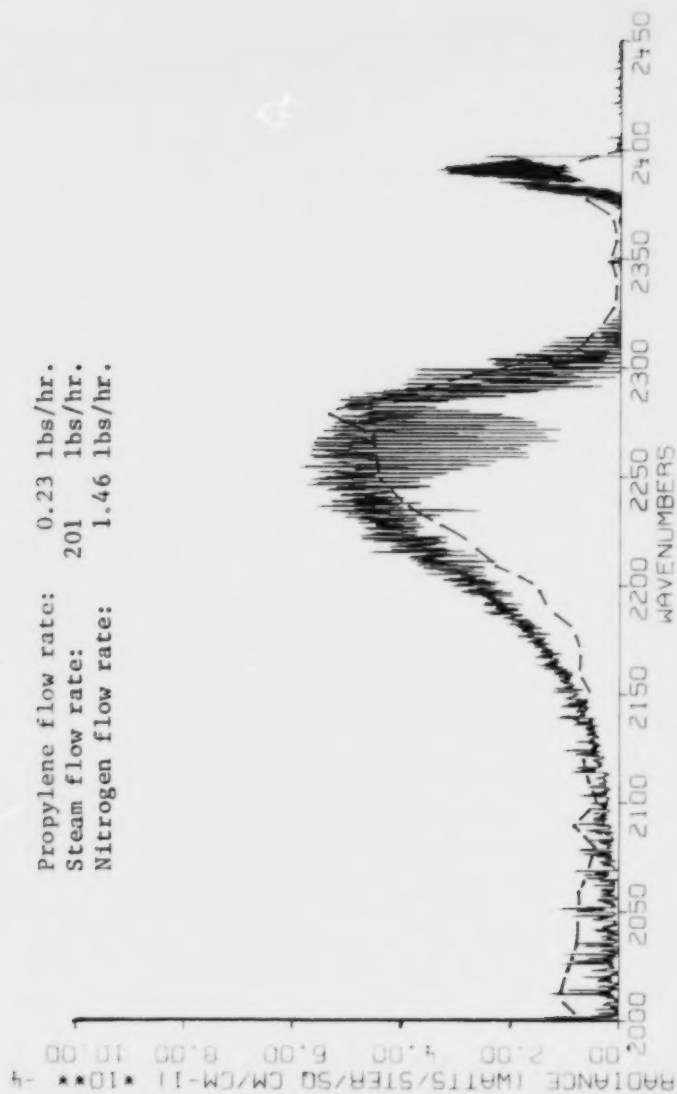


Figure 17. Observed and calculated flare radiances for test 53.  
 Deduced temperature = 1400K with 2900 ppm CO<sub>2</sub> and  
 27 ppm CO.

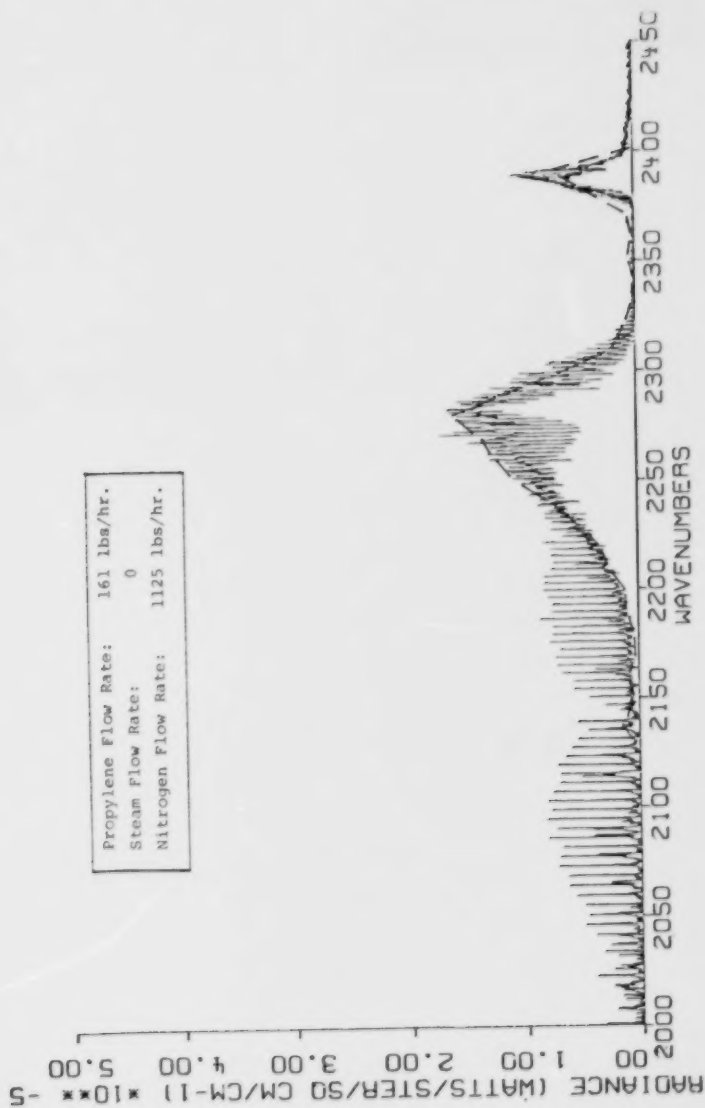


Figure 18. Observed and calculated flare radiances for test 55.  
Deduced temperature 683K with 1800 ppm CO<sub>2</sub>.

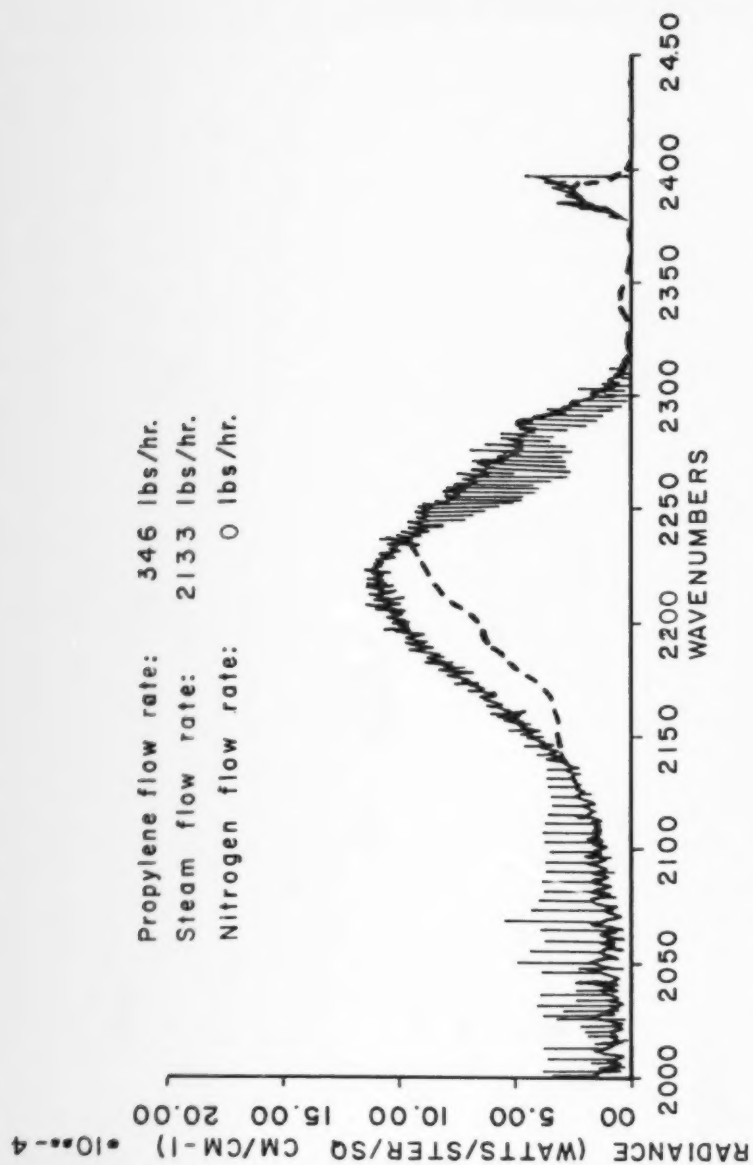


Figure 19. Observed and calculated flare radiance for test 59.  
Deduced temperature = 2500 K with > 6000 ppm CO<sub>2</sub>.

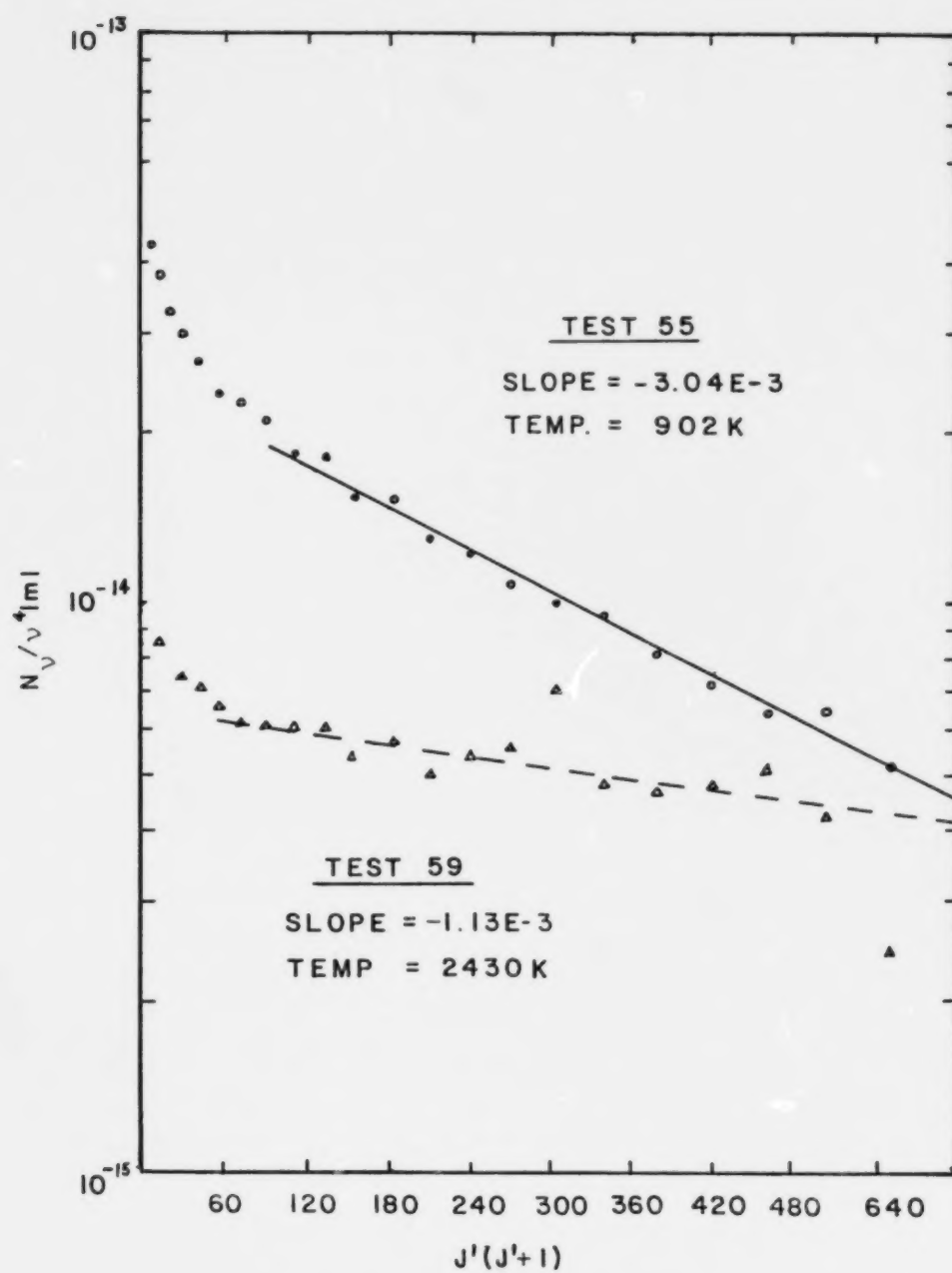


Figure 20. Temperature estimates from CO intensities.

TABLE 8. EXTRACTIVE PROBE DATA (14)

| <u>A. Continuous Samples</u> |          |          |          |          |
|------------------------------|----------|----------|----------|----------|
| Test No                      | 50       | 53       | 55       | 59       |
| OMI No.:                     | 50       | 68       | 89       | 129      |
| Time - Begin:                | 14:09:36 | 16:25:45 | 14:05:13 | 21:48:25 |
| Time - End:                  | 14:10:28 | 16:26:26 | 14:08:18 | 21:51:42 |
| Temp. (K):                   | 415      | 387      | 343      | 421      |
| CO (ppm):                    | 35.04    | 17.9     | 124.6    | 79.9     |
| CO <sub>2</sub> (ppm):       | 5382     | 2438     | 1371     | 5965     |
| THC (ppm):                   | 16.8     | 7.0      | 475.3    | 62.9     |
| O <sub>2</sub> (%)           | 20.10    | 19.38    | 20.85    | 19.26    |
| SO <sub>2</sub> (ppm)        | 0.040    | 0.648    | 0.085    | 0.039    |
| NO <sub>x</sub> (ppm):       | 0.60     | 1.10     | 0.13     | 1.30     |
| EFF. (%):                    | 99.06    | 98.98    | 69.68    | 97.69    |
| Amb. Temp. (K):              | 301      | 303      | 304      | 295      |
| Wind (mph):                  | 1.8      | 2.6      | 2.3      | 0.8      |
| Bkg. CO (ppm):               | 0.1      | 0.3      | 0.2      | 0.0      |
| Bkg. CO <sub>2</sub> (ppm):  | 415      | 375      | 515      | 421      |
| Bkg. THC (ppm):              | 5.4      | 5.7      | 6.8      | 2.9      |
| Bkg. O <sub>2</sub> (ppm):   | 20.81    | 20.50    | 21.23    | 20.61    |
| Bkg. SO <sub>2</sub> (ppm):  | 0.009    | 0.050    | 0.016    | 0.002    |
| Bkg. NO <sub>x</sub> (ppm):  | 0.12     | 0.14     | 0.78     | 0.18     |

(continued)

TABLE 8 (continued)

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| <u>B. Instantaneous Samples</u> |          |          |          |          |
|---------------------------------|----------|----------|----------|----------|
| Test No.:                       | 50       | 53       | 55       | 59       |
| OMI No.:                        | 50       | 68       | 89       | 129      |
| Methane (ppm):                  | 4.45     | 3.38     | 14.07    | 4.09     |
| Ethane/Ethylene (ppm):          | 1.77     | 0.63     | 3.35     | 1.89     |
| Acetylene (ppm):                | 0.88     | 0.25     | 0.20     | 0.51     |
| Propane (ppm):                  | 0.76     | 2.23     | 268      | 3.97     |
| Propylene (ppm):                | 3.29     | 9.13     | 1075     | 1.63     |
| Time:                           | 14:11:08 | 16:26:49 | 14:16:29 | 21:48:18 |

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| <u>C. Integrated Bag Samples</u> |                 |                 |                 |                 |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|
| Test No.:                        | 50              | 53              | 55              | 59              |
| OMI No.:                         | 50              | 68              | 89              | 129             |
| Methane (ppm):                   | 4.27            | 4.05            | 16.9            | 4.89            |
| Ethane/Ethylene (ppm):           | 3.57            | 4.05            | 40.8            | 9.10            |
| Acetylene (ppm):                 | 1.22            | 0.53            | 23.2            | 2.85            |
| Propane (ppm):                   | 4.94            | 3.99            | 277             | 13.4            |
| Propylene (ppm):                 | 20.7            | 17.0            | 1141            | 57.5            |
| Time:                            | 14:03-<br>14:11 | 16:25-<br>16:38 | 11:09-<br>11:16 | 21:47-<br>21:54 |

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- 2) spatial inhomogeneities within the field of view,
- 3) measurement noise inherent in the system, and
- 4) accuracy of the computer models and their data bases as used for analysis.

It is difficult to assess the contributions of these individual factors to the present FTIR results because of the limited data available. However, the comparisons of CO<sub>2</sub> concentrations made on tests 50 and 55 show a difference between probe and FTIR results of only 15 to 30 percent. This is seen as very good agreement since one would expect differences due to the two distinct measurement techniques used, particularly considering the local nature of the probe measurement and the integrated nature of the FTIR approach. The recommended future work outlined in Section 2 and Appendix B addresses this accuracy question further.

With regard to CO, one quantitative indication of its concentration detectability is obtained by noting that at a 20 ppm level it is computed to give peak emissions just equal to the noise peaks in the measurements (e.g., test 50). Concentrations two to three times this level should therefore be reliably detectable. The detectability of methane was similarly calculated to be approximately 600 ppm based on a noise equivalent radiance level of 1  $\mu\text{watt}/\text{cm}^2 \text{ ster cm}^{-1}$ . This exceeds even the 500 ppm level of methane resulting in the very low efficiency (70%) run of test 55. It should be pointed out, however, that these values are dependent on the physical size (cross section) of the flare under test and would consequently be substantially lower for large industrial flares. The magnitude of the CO<sub>2</sub> concentration is sufficiently large that its minimum detectability is not of concern even for small flares.

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11. Clough, S.A., F. X. Kneizys, L.S. Rothman, and W.O. Gallery, Atmospheric Spectral Transmittance and Radiance: FASCOD1B, Atmospheric Transmission, Vol. 277, Society of Photographic Instrumentation Engineers, Bellingham, WA, 1981.
12. McDaniel, M.D., private communication
13. McDaniel, M.D., op cit
14. McDaniel, M.D., ibid

## APPENDIX A

### INFRARED ANALYSIS OF "UNKNOWN" CALIBRATION GASES

A set of "unknown" gases were analyzed to assist in demonstrating the basic applicability of FTIR to gas detection and to supply a purely instrumental comparison between the ROSE system and the monitoring equipment of engineering science.

These gases were provided by Engineering Science, who later provided the known identifications and concentrations of the samples for comparison. The following procedure was used by our consultant, Dr. William Herget of Nicolet Instrument Company to analyze the samples (as described in his memo of July 28, 1982).

Five "unknown" samples of ES calibration gases were provided and spectra of each were obtained with the ROSE system after filling an evacuated one-meter cell with each sample. These spectra were calibrated using previously measured ROSE system calibration spectra.

The first sample analyzed contained 50 ppm of CH<sub>4</sub>. This was calibrated with the ROSE system using a previously recorded ambient air spectrum. The calculated concentration, therefore, depended on the ambient air concentration (which was not measured separately). The results were 40 ppm (based on an ambient CH<sub>4</sub> concentration of 1.5 ppm) or 52 ppm (based on an ambient CH<sub>4</sub> concentration of 2.0 ppm). The CH<sub>4</sub> spectrum was not analyzed further.

The other four sample spectra were brought back to Nicolet on disk, where the concentration calculation was carried out using a computer program that does a least squares fit between the peak heights of lines in a reference (calibration) spectrum with those in a sample spectrum.

The results were:

| <u>Sample #</u> | <u>Species</u>  | <u>ES Value</u>    | <u>Calculated Value (ppm)</u> | <u>% Difference</u> |
|-----------------|-----------------|--------------------|-------------------------------|---------------------|
| 2               | NO              | 17.6               | 15.2                          | 13.6                |
| 3               | CO <sub>2</sub> | $5.01 \times 10^4$ | $4.69 \times 10^4$            | 6.4                 |
| 5               | CO              | $3.49 \times 10^3$ | $3.17 \times 10^3$            | 9.2                 |

No species were observed in Sample #4. This sample was a "low ppm"  $\text{NO}_x$  mixture which was below the sensitivity of the ROSE system for a one-meter cell. The calibration and sample spectra for samples 2, 3 and 5 are shown in Figures A1, A2 and A3, respectively. The printout of the concentration calculation is also shown. (The potential  $\text{H}_2\text{O}$  interference lines in the NO and  $\text{CO}_2$  spectra have been replaced by straight line segments).

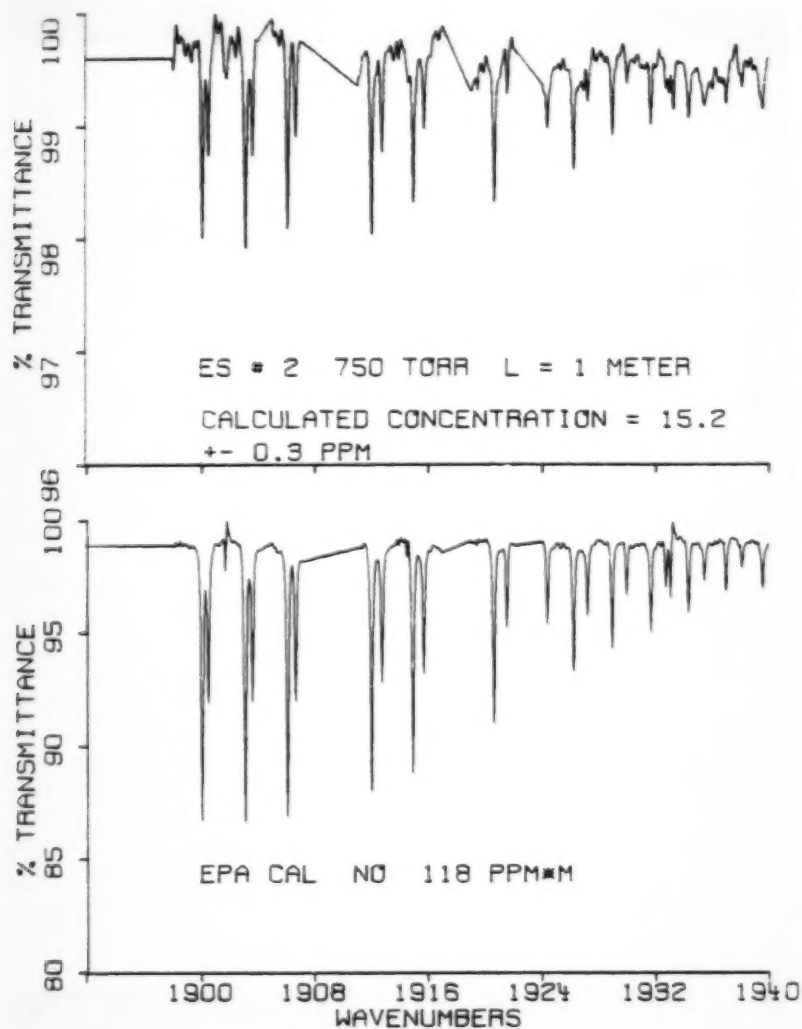


Figure A-1. ES sample #2 (NO).

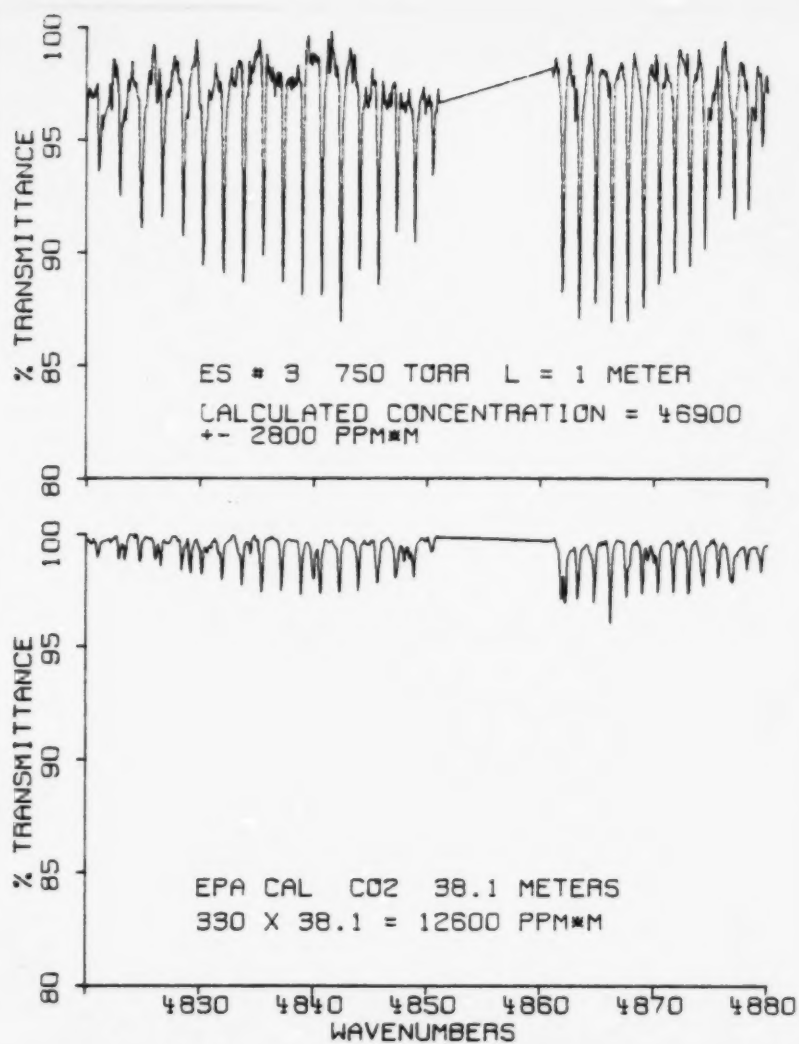


Figure A-2. ES sample #3 (CO<sub>2</sub>).

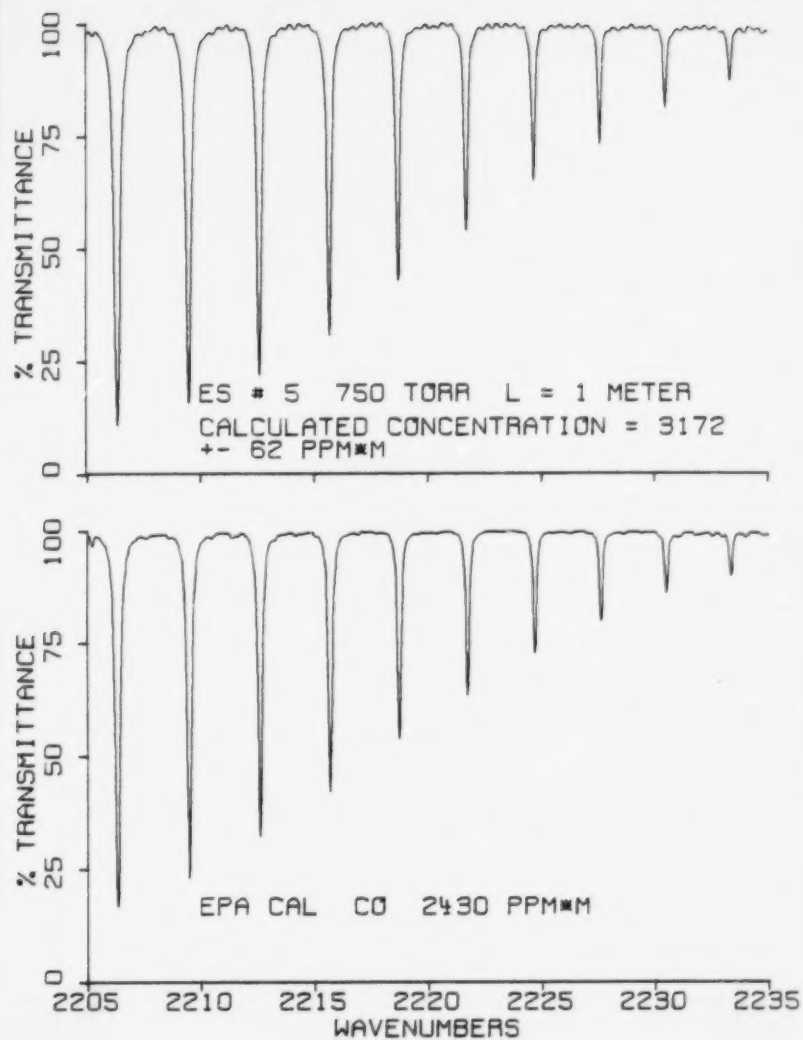


Figure A-3. ES sample #5 (CO).

## APPENDIX B

### RECOMMENDED FURTHER WORK TO IMPROVE AND VERIFY METHODOLOGY

As outlined in the text, a number of critical issues have been identified as needing further attention in fully developing an infrared method for analysis of flare efficiency. These are outlined here as are possible measurement programs capable of addressing these issues.

1) Comparison of extractive probe to FTIR results for temperature and concentration:

Although the concentrations obtained by the FTIR and probe techniques compared reasonably well ( 25%), the gas temperatures vary radically (350 K versus 680 K, for example). Since both techniques have potential field application, it is important to resolve these differences using a series of simultaneous tests under better controlled and instrumented conditions than those available for the current program.

2) Local versus spatially averaged measurements:

Because the FTIR instrument typically samples a significant volume of the gas over a complete line of sight through the plume, it performs a spatial averaging. This spatial averaging is advantageous since it minimizes the effects of local vortices or flame motion and gives a more "global" measure of the total emissions. However, the analysis of such spatially averaged data is difficult unless accurate specie concentration and temperature distributions are known for the plume. It is essential, therefore, that measurements be made to determine distribution functions for "typical" or specific flares under carefully controlled conditions.

3) Verification of absorption coefficients:

The determination of specie concentrations and flare efficiency requires accurate knowledge of absorption coefficients for each gas of significance (that is, its absorption per unit path length, per unit partial pressure). Uncertainties in these values are translated directly into uncertainties in resultant concentrations.

Consequently, laboratory measurements should be made on the uncertain absorption coefficients for significant plume species. These should be done at concentrations and temperatures representative of actual flare conditions. These measurements

then will provide data for verification of current values and/or refinement of those known to be in error.

4) Sensitivity of FTIR to gas properties, flow rates, etc.:

Further tests or analyses of infrared monitoring techniques should:

- a) consider a wider range of gases typically flared by the petroleum and chemical industries, as well as by blast furnaces, or other industrial sources in order to evaluate the applicability of FTIR to these cases;
- b) study flares of varying size and tip design to determine the generality of the successes and shortcomings found in the present study;
- c) cover a range of flow rates to determine how this affects the resultant IR signal; and
- d) investigate the possible use of tracer gases whose infrared signatures could be used for determining a dilution factor.

5) Predictive model development:

Empirical data should also be combined with theory to develop a predictive model rapid, compact, and general enough to be used routinely for evaluation of flare efficiencies in the field as well as to extrapolate the observed infrared signatures to other flare designs and measurement scenarios.

6) Measurement techniques:

The EPA ROSE spectrometer system employed to date is a general purpose research instrument. It is expected that the results of the measurement activities in 1) through 5) above will suggest ways in which the instrumentation can be tailored to the particular problem of flare efficiency monitoring while indicating alternative instrumentation or additional measurement methods.

A concentrated effort geared to the design of an optimum measurement system, tailored specifically to flare efficiency monitoring should be considered.

An analysis scheme by which the results of further tests could be used to answer these and additional questions are shown in Figures B-1 through B-5. Both probe and infrared methods would be used with infrared being used in both absorption and emission modes. Ideally, these tests should be conducted under

more controlled conditions than those described in Section 3. In particular, it would be beneficial to better define the volume of the plume actually observed, actually measure its temperature and gradients, and restrict as much as possible the effects of the wind, found to be a problem at John Zink Company.

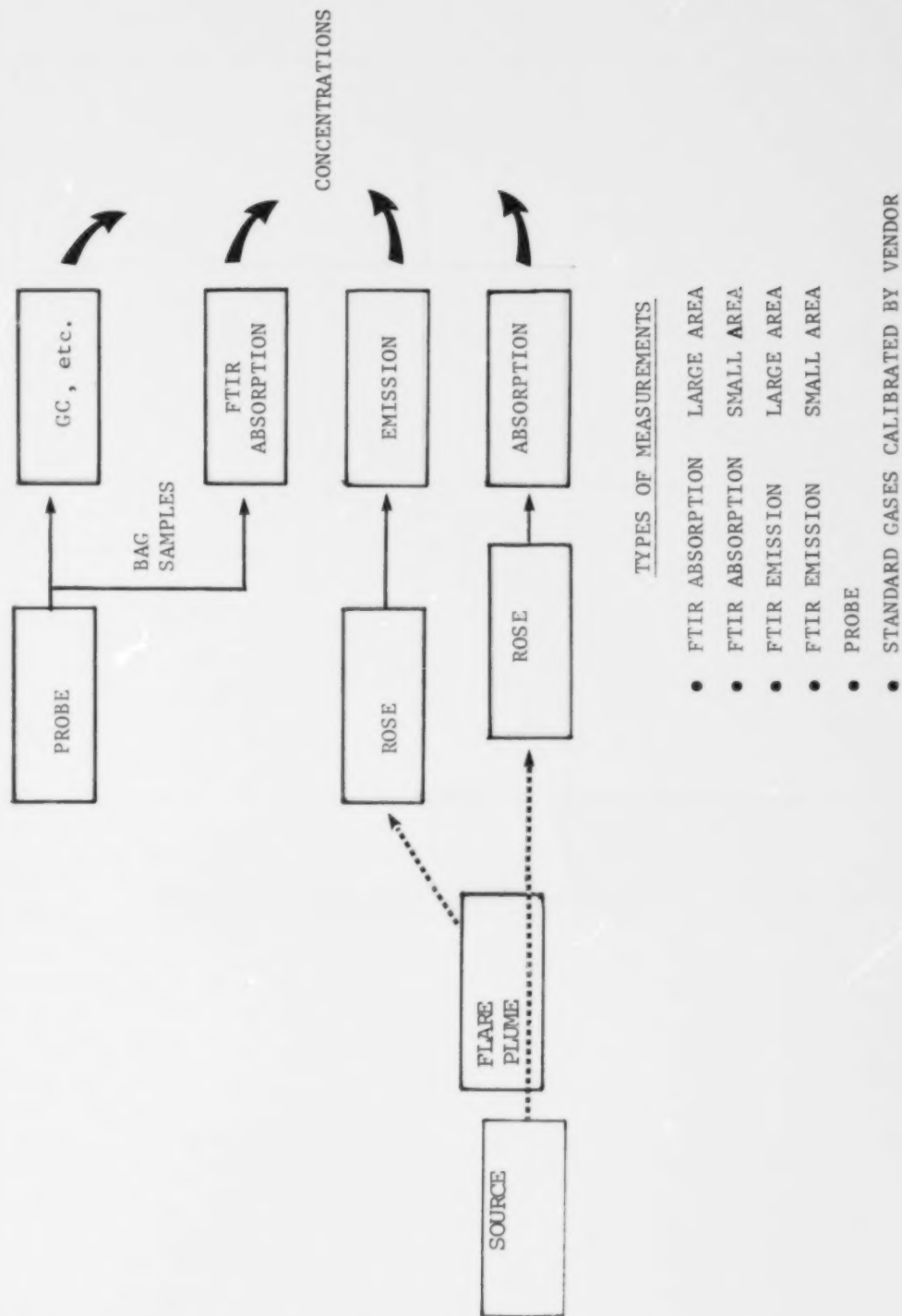


Figure B-1. Analysis scheme for future tests. Matrix of measurements.

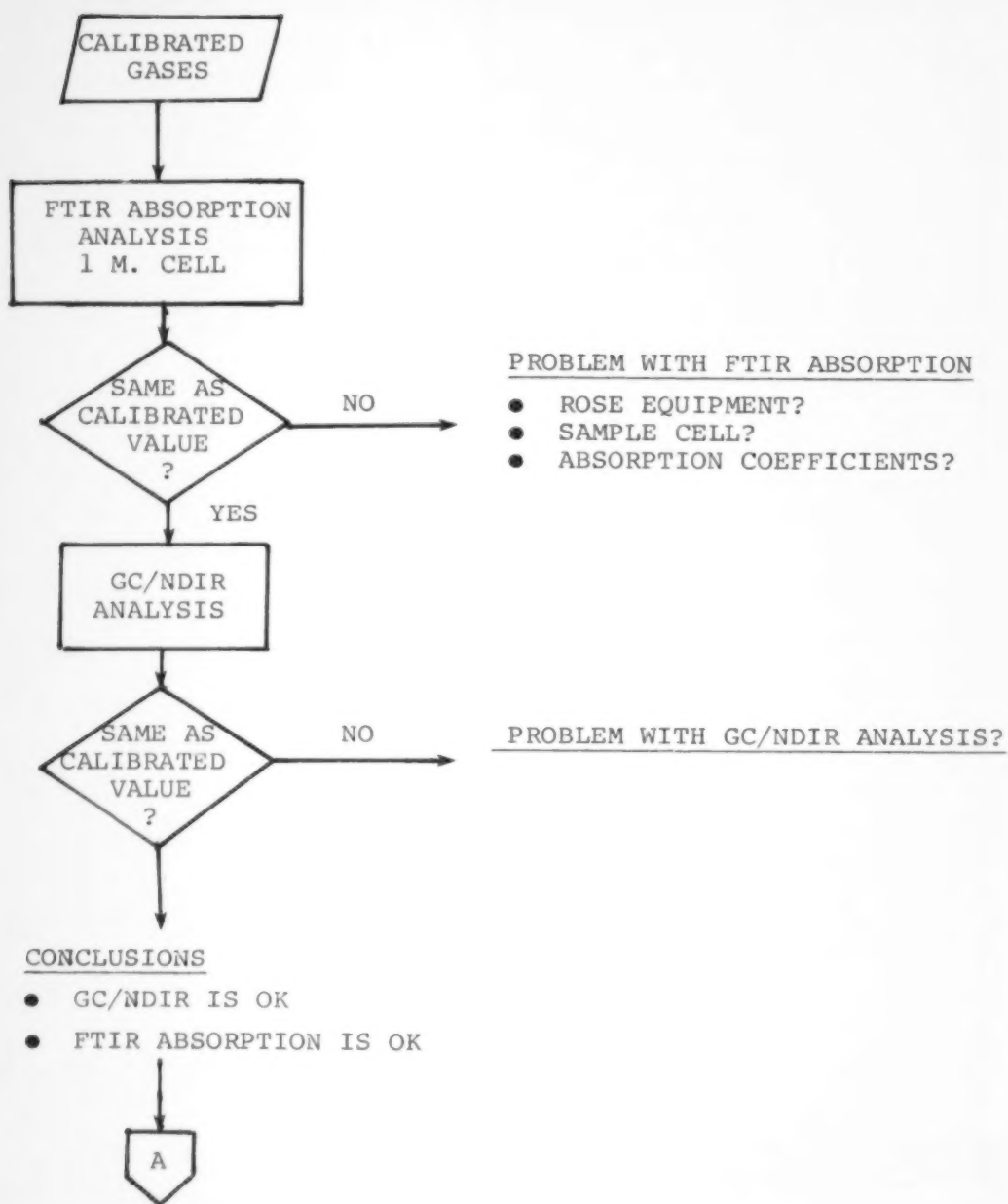


Figure B-2. Analysis scheme to provide base-line comparison between FTIR and GC/NDIR used for extractive probe.

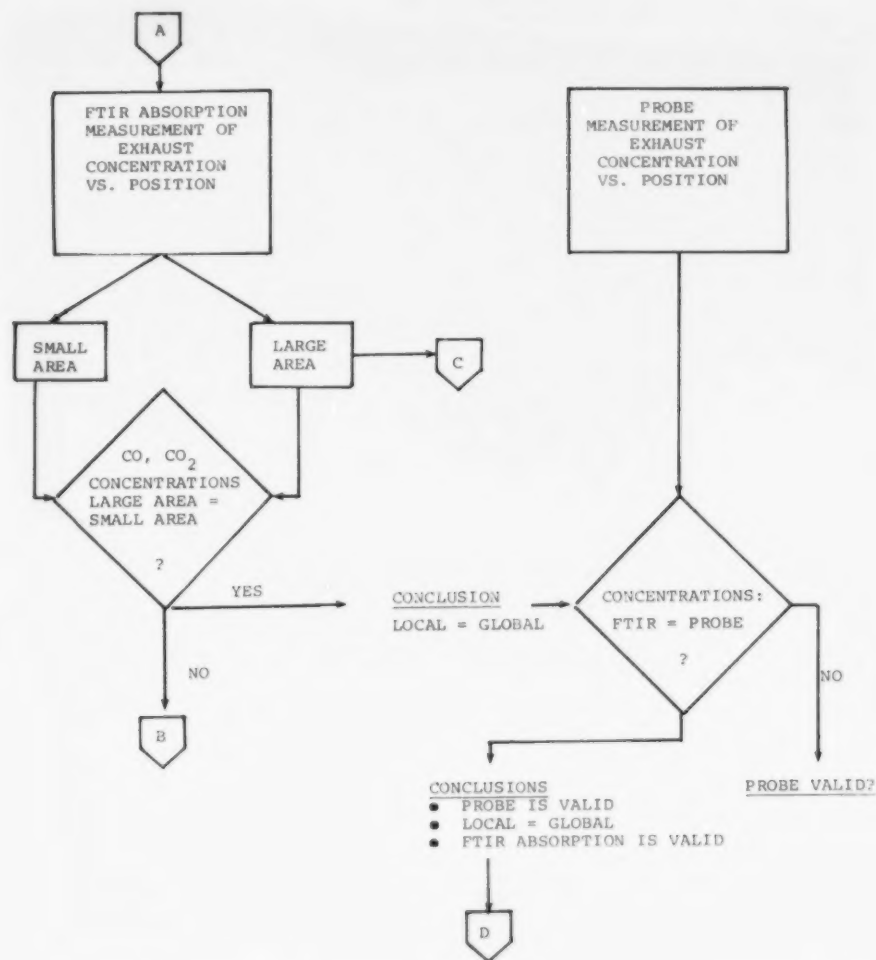


Figure B-3. Analysis scheme to determine if local concentrations represent global values to validate probe and FTIR, and measure spatial profile.

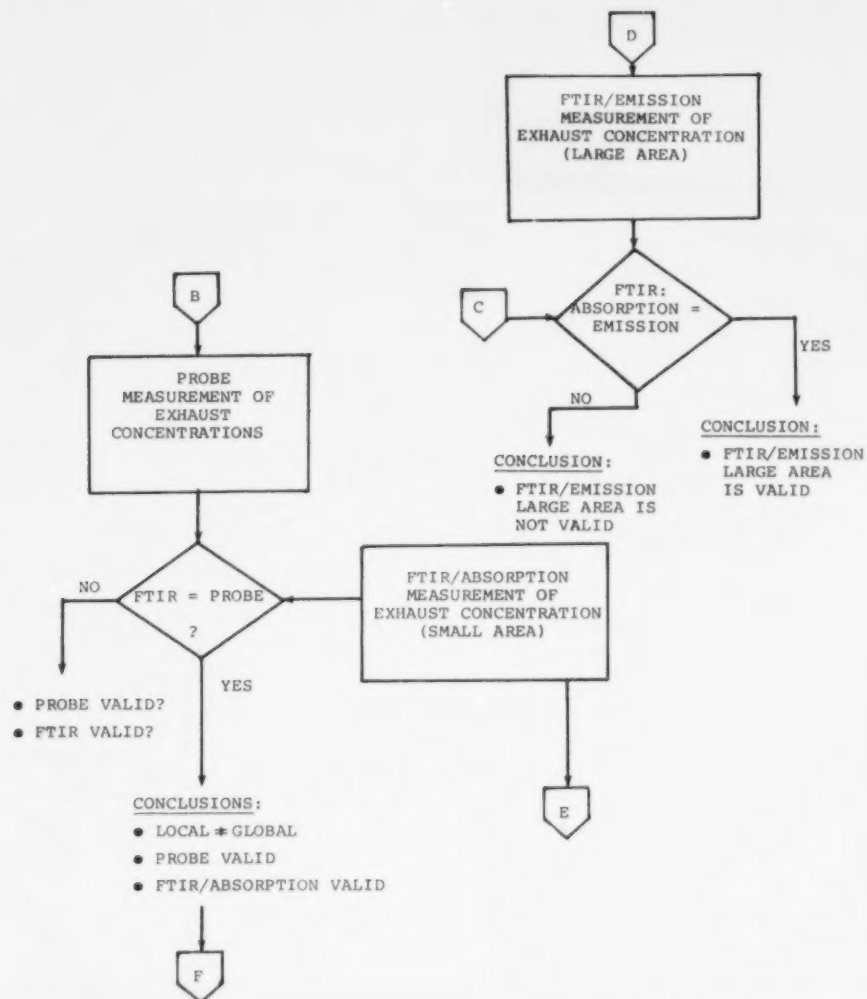


Figure B-4. Analysis scheme to determine if FTIR in absorption gives same concentrations as probe and to determine if FTIR/emission for large area is valid.

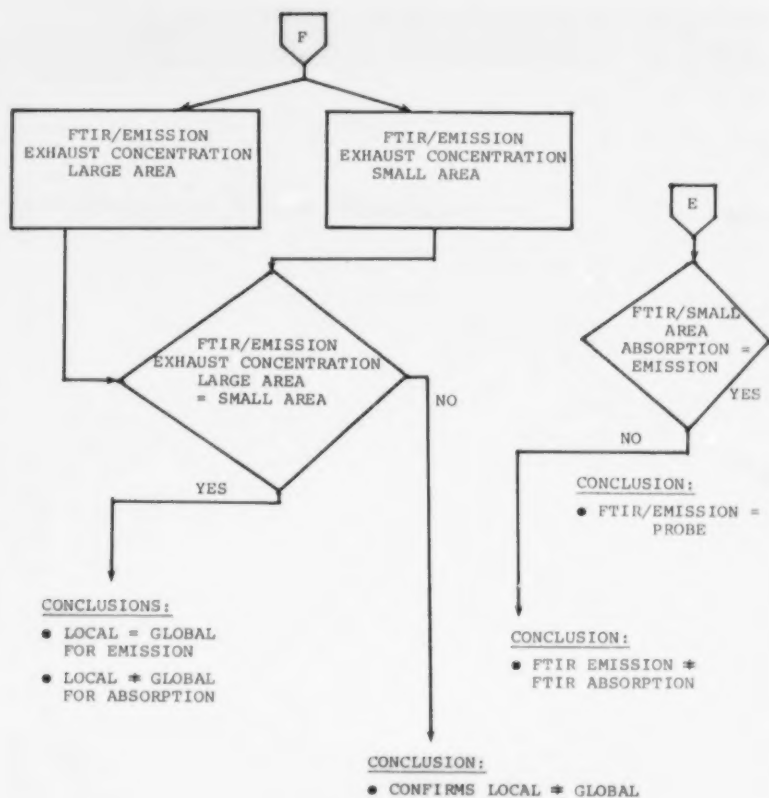


Figure B-5. Analysis scheme to determine if local and global FTIR emission data are equivalent and if FTIR is equivalent to probe values.

## GLOSSARY

**ATLES:** Atmospheric Transmission for Line Emission Sources, a computer code which produces predicted spectra containing bands of infrared emission lines for a given molecule in a volume of gas.

**"blue spike":** An informal term given to that portion of the infrared spectrum of carbon dioxide emission which lies in the optical frequency region between 2375 and 2400 wave numbers.

**combustion zone:** That portion of the plume produced by a flare within which combustion is taking place.

**dipole moment:** Non-uniform electric field associated with an atom or molecule resulting from the non-uniform charge distribution within it.

**extraction probe:** A device to extract samples of various gases and particulates from the flare plume for analysis.

**FASCOD1:** Fast Atmospheric Signature Code - A computer code which generates predicted spectra containing individual emission lines for a given molecule in a volume of gas.

**flare efficiency:** The degree of gaseous and particulate combustion products produced by a flare.

**flare plume:** A volume of gaseous and particulate combustion products produced by a flare.

**Fourier transform infrared spectrometer:** A device for measuring radiation spectra in which the device performs a Fourier transform on the radiation.

**Gaussian profile:** A defined mathematical relationship between the value of a parameter, for example, temperature or concentration, and the location of the source being so described, relative to a reference position.

**infrared-active:** The ability of a source to radiate a characteristic spectrum in the invisible portion of the electromagnetic spectrum that lies between approximately 10 and 14,000 wavenumbers.

**infrared spectroscopy:** The measurement of the ability of matter to absorb, transmit or reflect infrared radiation and the relating of the resultant data to chemical structure.

**interferometer:** A device which uses the principles of constructive and destructive interference of light in such a way as to perform a Fourier analysis on that light.

**optical background:** Optical background from sources either behind, to the side of or in front of the source of interest.

**passive remote sensing:** A technique that uses the self-emitted electromagnetic energy from a source for non-contact examination of that source (generally from a great distance).

**"red spike":** An informal term given to that portion of the infrared spectrum of carbon dioxide emission which lies between 2200 and 2325 wavenumbers.

**roll-off:** Refers to the shape of a Gaussian distribution and is dictated by one of the parameters (half-width,  $a$ ).

**Planck function:** A mathematical relationship between the electromagnetic energy which is emitted by a source at a certain optical frequency and the temperature of that source; included are the speed of light, Planck's Constant and Boltzmann's Constant.

**wavenumber:** The number proportional to the wavelength of a harmonic wave.